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# Field Tests of Industrial Stoker Coal-Fired Boilers for Emissions Control and Efficiency Improvement - Site J

KVB, Inc.
Minneapolis, MN

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

May 80

U.S. Department of Commerce
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**ABMA** American Boiler Manufacturers Association, 1500 Wilson Boulevard, Arlington VA 22209

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**EPA** United States Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park NC 27711

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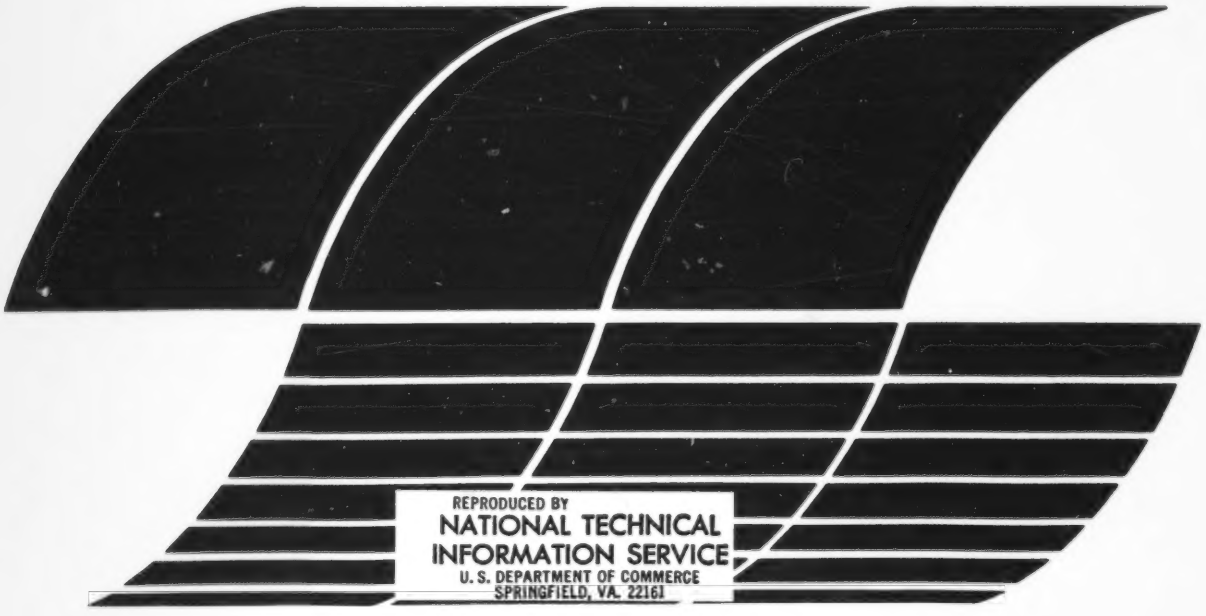
May 1980

# Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement — Site J

## Interagency Energy/Environment R&D Program Report



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16. ABSTRACT The report gives results of field measurements made on a 70,000 lb steam/hr coal-fired overfeed stoker with chain grate. The effects of various parameters on boiler emissions and efficiency were studied. Parameters include overfire air, excess oxygen, grate heat release, and coal properties. Measurements include O2, CO2, NO, SO2, SO3, uncontrolled and controlled particulate mass loading, and combustible content of the ash. In addition to test results and observations, the report describes the facility tested, coals fired, test equipment, and procedures. Full-load uncontrolled particulate loading on this unit averaged 0.89 lb/million Btu, while full-load controlled particulate loading averaged 0.20 lb/million Btu. Full-load NO emissions averaged 0.36 lb/million Btu.

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| Boilers | Efficiency | Stationary Sources | 13A | |
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| Coal | Fly Ash | Spreader Stokers | 21D | |
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by

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| | |
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| T. Davis | Combustion Engineering |
| N. H. Johnson | Detroit Stoker |
| K. Luuri | Riley Stoker |
| D. McCoy | E. Keeler Company |
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| R. A. Santos | Zurn Industries |

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Finally, our gratitude goes to the host boiler facilities which invited us to test their boiler. At their request, the facilities will remain anonymous to protect their own interests. Without their cooperation and assistance this program would not have been possible.

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## 1.0 INTRODUCTION

The principal objective of the test program described in this report, one of several reports in a series, is to produce information which will increase the ability of boiler manufacturers to design and fabricate stoker boilers that are an economical and environmentally satisfactory alternative to oil-fired units. Further objectives of the program are to: provide information to stoker boiler operators concerning the efficient operation of their boilers; provide assistance to stoker boiler operators in planning their coal supply contracts; refine application of existing pollution control equipment with special emphasis on performance; and contribute to the design of new pollution control equipment.

In order to meet these objectives, it is necessary to define stoker boiler designs which will provide efficient operation and minimum gaseous and particulate emissions, and define what those emissions are in order to facilitate preparation of attainable national emission standards for industrial size, coal-fired boilers. To do this, boiler emissions and efficiency must be measured as a function of coal analysis and sizing, rate of flyash reinjection, overfire air admission, ash handling, grate size, and other variables for different boiler, furnace, and stoker designs.

A field test program designed to address the objectives outlined above was awarded to the American Boiler Manufacturers Association (ABMA), sponsored by the United States Department of Energy (DOE) under contract number EF-77-C-01-2609, and co-sponsored by the United States Environmental Protection Agency (EPA) under inter-agency agreement number IAG-D7-E681. The program is directed by an ABMA Stoker Technical Committee which, in turn, has subcontracted the field test portion to KVB, Inc., of Minneapolis, Minnesota.

This report is the Final Technical Report for the tenth of eleven boilers to be tested under the ABMA program. It contains a description of the facility tested, the coals fired, the test equipment and procedures, and the results and observations of testing. There is also a data supplement to this report containing the "raw" data sheets from the tests conducted. The data supplement has the same EPA report number as this report except that it

is followed by "b" rather than "a". As a compilation of all data obtained at this test site, the supplement acts as a research tool for further data reduction and analysis as new areas of interest are uncovered in subsequent testing.

At the completion of this program, a final technical report will combine and correlate the test results from all sites tested. A report containing operating guidelines for boiler operators will also be written, along with a separate report covering trace species data. These reports will be available to interested parties through the National Technical Information Service (NTIS) or through the EPA's Technical Library.

Although it is EPA policy to use S.I. units in all EPA sponsored reports, an exception has been made herein because English units have been conventionally used to describe boiler design and operation. Conversion tables are provided in the Appendix for those who prefer S.I. units.

To protect the interests of the host boiler facilities, each test site in this program has been given a letter designation. As the tenth site tested, this is the Final Technical Report for Test Site J under the program entitled, "A Testing Program to Update Equipment Specifications and Design Criteria for Stoker Fired Boilers."

## 2.0 EXECUTIVE SUMMARY

A coal fired traveling grate stoker rated at 70,000 lbs steam/hr was extensively tested for emissions and efficiency between June 3 and June 30, 1979. This section summarizes the results of these tests and provides references to supporting figures, tables and commentary found in the main text of the report.

UNIT TESTED: Described in Section 3.0, page 9.

- E. Keeler Company Boiler

  Built 1977
  Type MKB
  70,000 lb/hr rated capacity
  150 psig operating pressure
  Saturated Steam

- Laclede Stoker

  Overfeed stoker
  Traveling grate
  One row overfire air jets on front wall

COALS TESTED: Individual coal analysis given in Tables 5-8, 5-9 and 5-10, pages 52-54. Commentary in Section 3.4, page 13, and Section 5.3, page 51.

- Ohio Coal

  13,117 Btu/lb
  7.85% Ash
  1.70% Sulfur
  3.59% Moisture
  2100°F Initial Ash Deformation Temperature

- Kentucky Coal

  13,607 Btu/lb
  6.57% Ash
  1.58% Sulfur
  2.24% Moisture
  2205°F Initial Ash Deformation Temperature

OVERFIRE AIR TEST RESULTS: Tests were conducted at various overfire air pressures ranging from less than 1" $H_2O$ to nearly 8" $H_2O$. Although these tests were not well defined, the relationship between this variable and boiler emissions and efficiency were examined with the following results. (Section 5.1, page 33)

- Particulate Loading

  Particulate loading increased whenever overfire air was increased. However, coal fines were also higher during the high overfire air tests. Therefore, the results are inconclusive. (Section 5.1.1, page 33)

- Nitric Oxide

  Nitric oxide emissions tended to increase as overfire air pressure increased. (Section 5.1.2, page 36)

- Boiler Efficiency

  Boiler efficiency decreased an average 2.0% when overfire air pressure was increased. (Section 5.1.3, page 37)

- Overfire Air Flow Rate

  Overfire air flow rate, as measured by a standard pitot tube, was shown to contribute 10% of the combustion air at full load, 8% $O_2$, and 8.5" $H_2O$ pressure at the jets. (Section 5.1.4, page 38)

- Carbon Monoxide

  The carbon monoxide monitor was out-of-service and, therefore, no CO data were obtained.

BOILER EMISSION PROFILES: Boiler emissions and efficiency were measured at loads of 50%, 75%, 85% and 100% of the units design capacity. The measured values are presented as functions of grate heat release and excess oxygen. (Section 5.2, page 38)

- Excess Oxygen Operating Levels

  The normal or "as-found" excess oxygen ranged from a low of 7.5% $O_2$ at full load to a high of 12.2% $O_2$ at 50% capacity. (Section 5.2.1, page 40)

- Particulate Loading

  At full load the uncontrolled particulate loading ranged from 0.70 lb/$10^6$Btu to 1.44 lb/$10^6$Btu. The uncontrolled particulate loading dropped off to as low as 0.37 lb/$10^6$Btu at 50% loading. However, the data is suspect due to sampling difficulties. The controlled particulate loading ranged from 0.18 to 0.23 lb/$10^6$Btu at full load, and dropped to as low as 0.11 lb/$10^6$Btu at 50% load. (Section 5.2.2, page 40)

- Nitric Oxide

  Nitric oxide concentration averaged 0.362 ±.052 lb/$10^6$Btu on this unit. It increased with increasing oxygen by 0.096 lb NO/$10^6$Btu/% $O_2$ at full load. At constant $O_2$, nitric oxide concentration increased with load. (Section 5.2.3, page 43)

- Combustibles in the Ash

  Combustible content of the uncontrolled flyash ranged from 24 to 36% and was invarient with load. Combustible content of the bottom ash ranged from 7 to 31% and tended to increase as load increased. (Section 5.2.4, page 47)

- Boiler Efficiency

  Boiler efficiency averaged 81.6% overall with five tests indicating efficiencies in the range 82.6% to 83.5%. (Section 5.2.5, page 47)

COAL PROPERTIES: Of the two coals tested, the Kentucky coal was considered a better coal than the Ohio coal because of its higher Btu content, and lower sulfur, ash and fines. The observed effect of these coals on emissions and efficiency were as follows. (Section 5.3.3, page 55)

- Particulate Loading

  Both coals produced similar particulate mass loadings. (Figures 5-5 and 5-6, pages 42 and 44)

- Nitric Oxide

  Both coals produced similar levels of nitric oxide. (Figures 5-7 and 5-8, pages 45 and 46)

- Sulfur Balance

  Of the sulfur in the Ohio coal, 90.6% was detected in the flue gas as $SO_2$ and $SO_3$, and 1.3% was detected in the bottom ash and flyash. Of the sulfur in the Kentucky coal, 121.4% was detected in the flue gas and 2.9% in the ash. The origin of the inaccuracies in the sulfur balance is very likely in the fuel sulfur determination. (Table 5-12, page 59)

- Combustibles in the Ash

  Combustibles in the bottom ash were invarient with coal. Combustibles in the flyash averaged 25% for Ohio coal and 31% for Kentucky coal. (Figures 5-9 and 5-10, pages 48 and 49)

- Boiler Efficiency

  Kentucky coal averaged 0.7% higher boiler efficiency than Ohio coal because of its lower moisture and hydrogen content. (Table 5-13, page 60)

PARTICLE SIZE DISTRIBUTION OF FLYASH: Four particle size distribution measurements of the flyash were made. They indicate that 25% of the uncontrolled flyash is smaller than 3 micrometers while 70 to 80% of the controlled flyash is smaller than 3 micrometers. (Section 5.4, page 60)

EFFICIENCY OF MECHANICAL DUST COLLECTOR: The average measured dust collector efficiency was 74.3%. The data is suspect for the same reason that the uncontrolled particulate loading data is suspect. (Section 5.5, page 63)

SOURCE ASSESSMENT SAMPLING SYSTEM (SASS): Flue gas was sampled for polynuclear aromatic hydrocarbons and trace elements during one full load test on each of the two coals. Data will be presented in a separate report at the completion of this test program. Section 5.6, page 63)

The Test Outline and Emission Data Summary are presented in Tables 2-1 and 2-2 on the following pages. For reference, additional data tables are included in Section 5.6. A "Data Supplement" containing all the unreduced data obtained at Site J is available under separate cover for those who wish to further analyze the data. The "Data Supplement" has the same EPA document number as this report except that it is followed by the letter "b" rather than "a". Copies of this report and the Data Supplement are available through EPA and the National Technical Information Service (NTIS).

TABLE 2-1

TEST OUTLINE FOR TEST SITE J

| FIRING CONDITIONS | | TEST MEASUREMENTS BY TEST NUMBER | | |
|---|---|---|---|---|
| % Boiler Capacity | Coal | Gaseous Emissions | Particulate Loading | Other Tests |
| 100 | Ohio | 3, 4, 5, 13, 14, 16 | 5, 14 | 16 SASS & SOx, 13 Brink |
| | Kentucky | 6, 15 | 6 | 15 SASS & SOx |
| 85 | Ohio | 7 | 7 | -- |
| | Kentucky | -- | -- | -- |
| 75 | Ohio | 2 | 2 | -- |
| | Kentucky | 8 | 8 | -- |
| 50 | Ohio | 1 | 1 | -- |
| | Kentucky | 9 | 9 | -- |

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TABLE 2-2

EMISSION DATA SUMMARY
TEST SITE J

| Test No. | Date | % Design Capacity | Coal* | Excess Air, % | $O_2$ % dry | $CO_2$ % dry | NO as $NO_2$ lb/$10^6$ Btu | NO ppm dry | SOx lb/$10^6$ Btu | Uncontrolled Particulate lb/$10^6$Btu | Controlled Particulate lb/$10^6$Btu |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 6/03/79 | 48 | 1 | 84 | 10.2 | -- | 0.398 | 291 | -- | 0.369 | 0.115 |
| 2 | 6/04/79 | 74 | 1 | 95 | 10.6 | 8.1 | 0.416 | 304 | -- | 0.779 | 0.188 |
| 3 | 6/05/79 | 100 | 1 | 52 | 7.5 | 10.4 | 0.316 | 231 | -- | -- | -- |
| 4 | 6/06/79 | 100 | 1 | 71 | 9.1 | 9.0 | 0.353 | 258 | -- | -- | -- |
| 5 | 6/12/79 | 103 | 1 | 56 | 7.9 | 10.2 | 0.393 | 287 | -- | 1.442 | 0.228 |
| 6 | 6/13/79 | 99 | 2 | 58 | 8.1 | 10.1 | 0.337 | 247 | -- | 0.699 | 0.182 |
| 7 | 6/14/79 | 85 | 1 | 66 | 8.7 | 9.6 | 0.378 | 276 | -- | 0.462 | 0.167 |
| 8 | 6/15/79 | 73 | 2 | 70 | 9.0 | 9.4 | 0.277 | 203 | -- | 0.574 | 0.114 |
| 9 | 6/16/79 | 50 | 2 | 129 | 12.2 | 7.0 | 0.418 | 306 | -- | 0.617 | 0.185 |
| 13 | 6/19/79 | 103 | 1 | 56 | 7.9 | 10.1 | 0.282 | 206 | -- | -- | -- |
| 14 | 6/20/79 | 97 | 1 | 68 | 8.8 | 9.9 | 0.383 | 280 | -- | 0.984 | 0.224 |
| 15 | 6/28/79 | 94 | 2 | 56 | 7.9 | 9.9 | 0.322 | 236 | 1.968 | -- | -- |
| 16 | 6/30/79 | 93 | 1 | 68 | 8.9 | 8.9 | 0.438 | 320 | 2.877 | -- | -- |

* 1 - Ohio Coal
2 - Kentucky Coal

## 3.0 DESCRIPTION OF FACILITY TESTED AND COALS FIRED

This section discusses the general physical layout and operational characteristics of the boiler tested at Test Site J. The coals utilized in this test series are also discussed.

### 3.1 BOILER J DESCRIPTION

Boiler J was manufactured by E. Keeler Company in 1977. It is a type MKB boiler designed for 250 psig, and capable of a maximum continuous capacity of 70,000 pounds of steam per hour at 150 psig and saturated temperature using feedwater at 220°F.

The unit has a Laclede stoker with a traveling grate. Coal is mass fed to the front end of the grate and ash is continuously discharged at the back end. There is no suspension burning. Undergrate air is controlled in six zones. Design data on the boiler and stoker are presented in Table 3-1.

The boiler is equipped with a multiclone dust collector and there is no flyash reinjection.

### 3.2 OVERFIRE AIR SYSTEM

The overfire air system on Boiler J consists of one row of air jets on the front wall. The jets are 3'10" above the grate and 30° below the horizontal. The overfire air is supplied by an independent fan. At maximum flow the pressure is about 10" $H_2O$.

### 3.3 TEST PORT LOCATIONS

Emission measurements were made at two locations -- at the boiler outlet (before the multiclone dust collector) and the dust collector outlet (stack). The locations of these sample sites are shown in Figure 3-1. Their geometry is shown in Figure 3-2.

TABLE 3-1

DESIGN DATA
TEST SITE J

| | | |
|---|---|---|
| BOILER: | Manufacturer | E. Keeler Company |
| | Type | MKB |
| | Boiler Heating Surface | 8,460 $ft^2$ |
| | Design Pressure | 250 psig |
| | Tube Diameter | 2-1/2 " |
| FURNACE: | Volume | 4,005 $ft^3$ |
| STOKER: | Manufacturer | Laclede |
| | Type | Traveling Grate |
| | Width | 14'0" |
| | Length | 15'3" |
| | Effective Grate Area | 213 $ft^2$ |
| HEAT RATES: | Steam Flow | 70,000 lb/hr |
| | Input to Furnace* | $76.7 \times 10^6$ Btu/hr |
| | Furnace Width Heat Release* | $5.48 \times 10^6$ Btu/hr-ft |
| | Grate Heat Release* | $360 \times 10^3$ Btu/hr-$ft^2$ |
| | Furnace Liberation* | $19.1 \times 10^3$ Btu/hr-$ft^3$ |

* The heat input and heat release rates were determined from coal feed rates and are not necessarily those of the manufacturer.

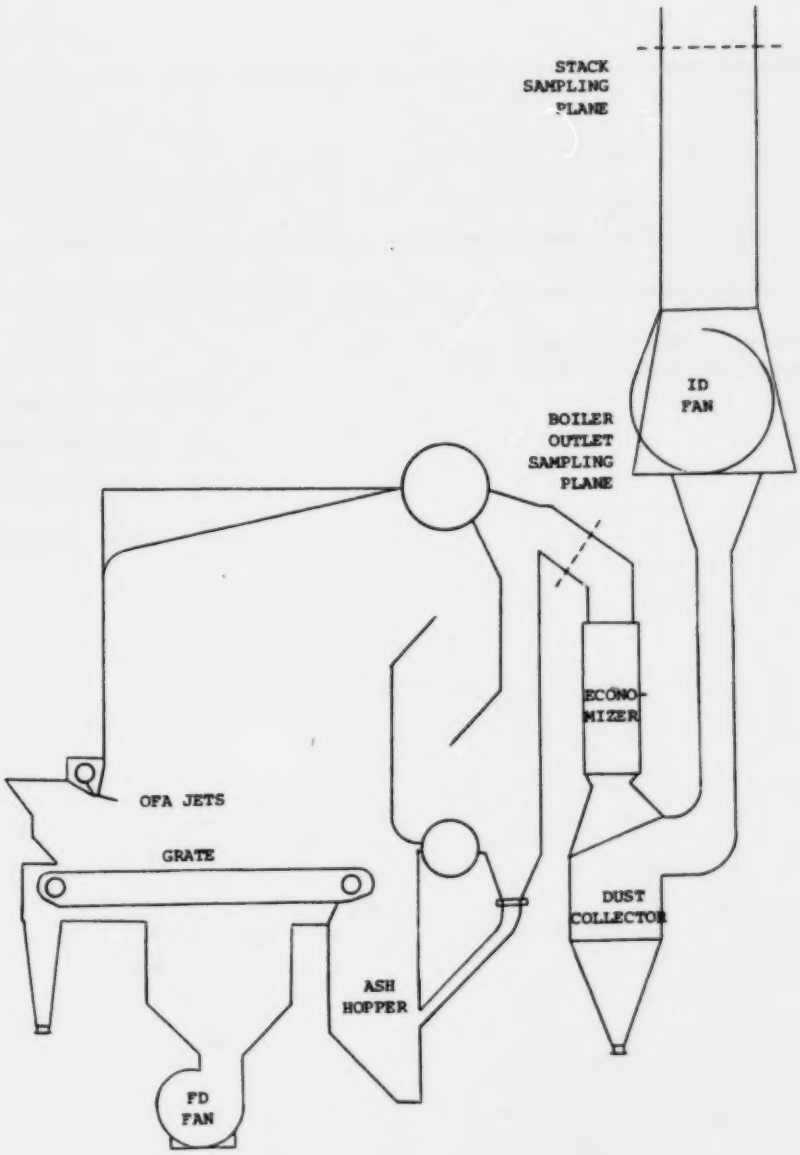


Figure 3-1. Boiler J Schematic

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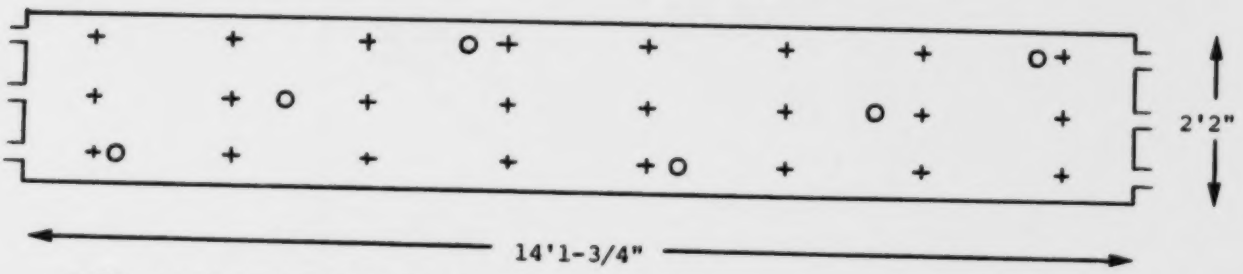
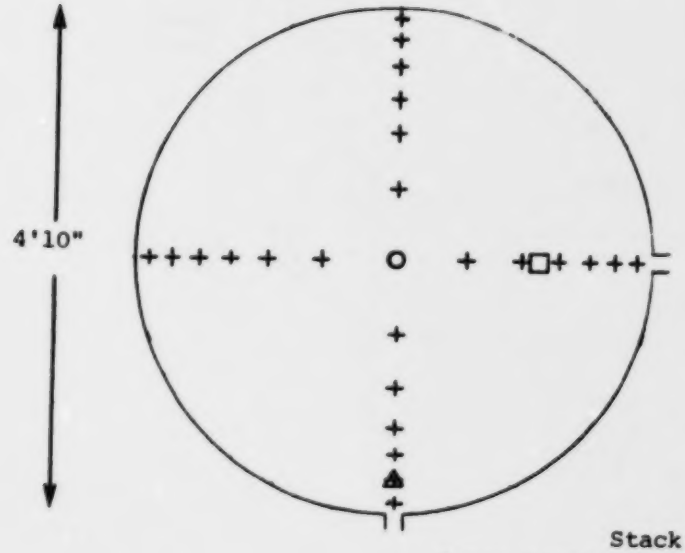



Boiler Outlet Sampling Plane
Cross Sectional Area = 30.65 $ft^2$

+ Particulate Sampling Points
O Gaseous Sampling Points
△ SOx Sampling Points
□ SASS Sampling Point




Stack Sampling Plane
Cross Sectional Area = 18.35 $ft^2$

Figure 3-2. Boiler J Sample Plane Geometry

Whenever particulate loading was measured, it was measured simultaneously at both locations using 24-point sample traverses. Gaseous measurements of $O_2$, $CO_2$, CO and NO were obtained by pulling samples individually and compositely from six probes distributed along the width of the boiler outlet and from one probe at the dust collector outlet. $NO_2$ and unburned hydrocarbons were measured by a heated sample line attached to one of the middle gaseous probes at the boiler outlet. SOx measurements and SASS samples for organic and trace element determinations were each obtained from single points within the dust collector outlet duct.

## 3.4 COALS UTILIZED

Two coals were test fired at Test Site J. These are referred to as Ohio coal and Kentucky coal in this report. The primary coal tested was the Ohio coal, which was supplied by C and W Mining (Columbiana County, Lisbon, Ohio). The secondary coal was a higher Btu coal and it was supplied by Island Creek Coal Company. It came from the Spurlock mine in Salisbury, Kentucky.

Coal samples were taken for each test involving particulate or SASS sampling. The average coal analyses obtained from these samples are presented in Table 3-2. The analyses of each individual coal sample are presented in Section 5.0, Test Results and Observations, Table 5-8, 5-9, and 5-10.

TABLE 3-2

AVERAGE COAL ANALYSIS
TEST SITE J

| | Ohio Coal | Kentucky Coal |
|---|---|---|
| **Proximate (As Rec'd)** | | |
| % Moisture | 3.59 | 2.24 |
| % Ash | 7.85 | 6.57 |
| % Volatile | 37.83 | 39.09 |
| % Fixed Carbon | 50.73 | 52.10 |
| Btu/lb | 13117 | 13607 |
| % Sulfur | 1.70 | 1.58 |
| **Ultimate (As Rec'd)** | | |
| % Moisture | 3.05 | 1.96 |
| % Carbon | 74.74 | 76.77 |
| % Hydrogen | 5.13 | 5.09 |
| % Nitrogen | 1.66 | 1.23 |
| % Chlorine | 0.19 | 0.13 |
| % Sulfur | 1.75 | 1.43 |
| % Ash | 7.05 | 7.25 |
| % Oxygen (diff) | 6.43 | 6.14 |

## 4.0 TEST EQUIPMENT AND PROCEDURES

This section details how specific emissions were measured and the sampling procedures followed to assure that accurate, reliable data were collected. Note that carbon monoxide (CO) was not measured at this test site due to problems with the CO monitor.

### 4.1 GASEOUS EMISSIONS MEASUREMENTS (NOx, CO, $CO_2$, $O_2$, HC)

A description is given below of the analytical instrumentation, related equipment, and the gas sampling and conditioning system, all of which are located in a mobile testing van owned and operated by KVB. The systems have been developed as a result of testing since 1970, and are operational and fully checked out.

#### 4.1.1 Analytical Instruments and Related Equipment

The analytical system consists of five instruments and associated equipment for simultaneously measuring the constituents of flue gas. The analyzers, recorders, valves, controls, and manifolds are mounted on a panel in the vehicle. The analyzers are shock mounted to prevent vibration damage. The flue gas constituents which are measured are oxides of nitrogen (NO, NOx), carbon monoxide (CO), carbon dioxide ($CO_2$), oxygen ($O_2$), and gaseous hydrocarbons (HC).

Listed below are the measurement parameters, the analyzer model furnished, and the range and accuracy of each parameter for the system. A detailed discussion of each analyzer follows:

| | |
|---|---|
| Constituent: | Nitric Oxide/Total Oxides of Nitrogen (NO/NOx) |
| Analyzer: | Thermo Electron Model 10 Chemiluminescent Analyzer |
| Range: | 0-2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm NO |
| Accuracy: | ±1% of full scale |

| | |
|---|---|
| Constituent: | Carbon Monoxide |
| Analyzer: | Beckman Model 315B NDIR Analyzer |
| Range: | 0-500 and 0-2000 ppm CO |
| Accuracy: | ±1% of full scale |

Constituent: Carbon Dioxide
Analyzer: Beckman Model 864 NDIR Analyzer
Range: 0-5% and 0-20% $CO_2$
Accuracy: ±1% of full scale

Constituent: Oxygen
Analyzer: Teledyne Model 326A Fuel Cell Analyzer
Range: 0-5, 10, and 25% $O_2$ full scale
Accuracy: ±1% of full scale

Constituent: Hydrocarbons
Analyzer: Beckman Model 402 Flame Ionization Analyzer
Range: 5 ppm full scale to 10% full scale
Accuracy: ±1% of full scale

Oxides of nitrogen. The instrument used to monitor oxides of nitrogen is a Thermo Electron chemiluminescent nitric oxide analyzer. The instrument operates by measuring the chemiluminescent reaction of NO and $O_3$ to form $NO_2$. Light is emitted when electronically excited $NO_2$ molecules revert to their ground state. The resulting chemiluminescence is monitored through an optical filter by a high sensitivity photomultiplier, the output of which is linearly proportional to the NO concentration.

Air for the ozonator is drawn from ambient air through a dryer and a ten micrometer filter element. Flow control for the instrument is accomplished by means of a small bellows pump mounted on the vent of the instrument downstream of a separator that prevents water from collecting in the pump.

The basic analyzer is sensitive only to NO molecules. To measure NOx (i.e., $NO+NO_2$), the $NO_2$ is first converted to NO. This is accomplished by a converter which is included with the analyzer. The conversion occurs as the gas passes through a thermally insulated, resistance heated, stainless steel coil. With the application of heat, $NO_2$ molecules in the sample gas are reduced to NO molecules, and the analyzer now reads NOx. $NO_2$ is obtained by the difference in readings obtained with and without the converter in operation.

Specifications: Accuracy 1% of full scale
Span stability ±1% of full scale in 24 hours
Zero stability ±1 ppm in 24 hours
Power requirements 115±10V, 60 Hz, 1000 watts
Response 90% of full scale in 1 sec. (NOx mode),
0.7 sec. NO mode
Output 4-20 ma

Sensitivity 0.5 ppm
Linearity ±1% of full scale
Vacuum detector operation
Range: 2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm full scale

Carbon monoxide. Carbon monoxide concentration is measured by a Beckman 315B non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the CO analyzer are 0-500 ppm and 0-2000 ppm. (Note: this intrument was out-of-service at Site J)

Specifications: Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma

Carbon dioxide. Carbon dioxide concentration is measured by a Beckman Model 864 short path-length, non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the $CO_2$ analyzer are 0-5% and 0-20%.

Specifications: Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma

Oxygen. The oxygen content of the flue gas sample is automatically and continuously determined with a Teledyne Model 326A Oxygen analyzer. Oxygen in the flue gas diffuses through a Teflon membrane and is reduced on the surface of the cathode. A corresponding oxidation occurs at the anode internally and an electric current is produced that is proportional to the concentration of oxygen. This current is measured and conditioned by the instrument's electronic circuitry to give a final output in percent $O_2$ by volume for operating ranges of 0% to 5%, 0% to 10%, or 0% to 25%.

Specifications:
- Precision ±1% of full scale
- Response 90% in less than 40 sec.
- Sensitivity 1% of low range
- Linearity ±1% of full scale
- Ambient temperature range 32-125°F
- Fuel cell life expectancy 40,000%-hours
- Power requirement 115 VAC, 50-60 Hz, 100 watts
- Output 4-20 ma

Hydrocarbons. Hydrocarbons are measured using a Beckman Model 402 hydrocarbon analyzer which utilizes the flame ionization method of detection. The sample is drawn to the analyzer through a heated line to prevent the loss of higher molecular weight hydrocarbons. It is then filtered and supplied to the burner by means of a pump and flow control system. The sensor, which is the burner, has its flame sustained by regulated flows of fuel (40% hydrogen plus 60% helium) and air. In the flame, the hydrocarbon components of the sample undergo a complete ionization that produces electrons and positive ions. Polarized electrodes collect these ions, causing a small current to flow through a circuit. This ionization current is proportional to the concentration of hydrocarbon atoms which enter the burner. The instrument is available with range selection from 5 ppm to 10% full scale as $CH_4$.

Specifications:
- Full scale sensitivity, adjustable from 5 ppm $CH_4$ to 10% $CH_4$
- Ranges: Range multiplier switch has 8 positions: X1, X5, X10, X50, X100, X5-0, X1000, and X5000. In addition, span control provides continuously variable adjustment within a dynamic range of 10:1
- Response time 90% full scale in 0.5 sec.
- Precision ±1% of full scale
- Electronic stability ±1% of full scale for successive identical samples

Reproducibility ±1% of full scale for successive identical samples
Analysis temperature: ambient
Ambient temperature 32°F to 110°F
Output 4-20 ma
Air requirements 350 to 400 cc/min of clean, hydrocarbon-free air, supplied at 30 to 200 psig
Fuel gas requirements 75 to 80 cc/min of pre-mixed fuel consisting of 40% hydrogen and 60% nitrogen or helium, supplied at 30 to 200 psig
Electrical power requirements 120V, 60 Hz
Automatic flame-out indication and fuel shut-off valve

### 4.1.2 Recording Instruments

The output of the four analyzers is displayed on front panel meters and are simultaneously recorded on a Texas Instrument Model FLO4W6D four-pen strip chart recorder. The recorder specifications are as follows:

Chart size 9-3/4 inch
Accuracy ±0.25%
Linearity <0.1%
Line voltage 120V±10% at 60 Hz
Span step response: one second

### 4.1.3 Gas Sampling and Conditioning System

The gas sampling and conditioning system consists of probes, sample lines, valves, pumps, filters and other components necessary to deliver a representative, conditioned sample gas to the analytical instrumentation. The following sections describe the system and its components. The entire gas sampling and conditioning system shown schematically in Figure 4-1 is contained in the emission test vehicle.

### 4.1.4 Gaseous Emission Sampling Techniques

Boiler access points for gaseous sampling are selected in the same sample plane as are particulate sample points. Each probe consists of one-half inch 316 stainless steel heavy wall tubing. A 100 micrometer Mott Metallurgical Corporation sintered stainless steel filter is attached to each probe for removal of particulate material.

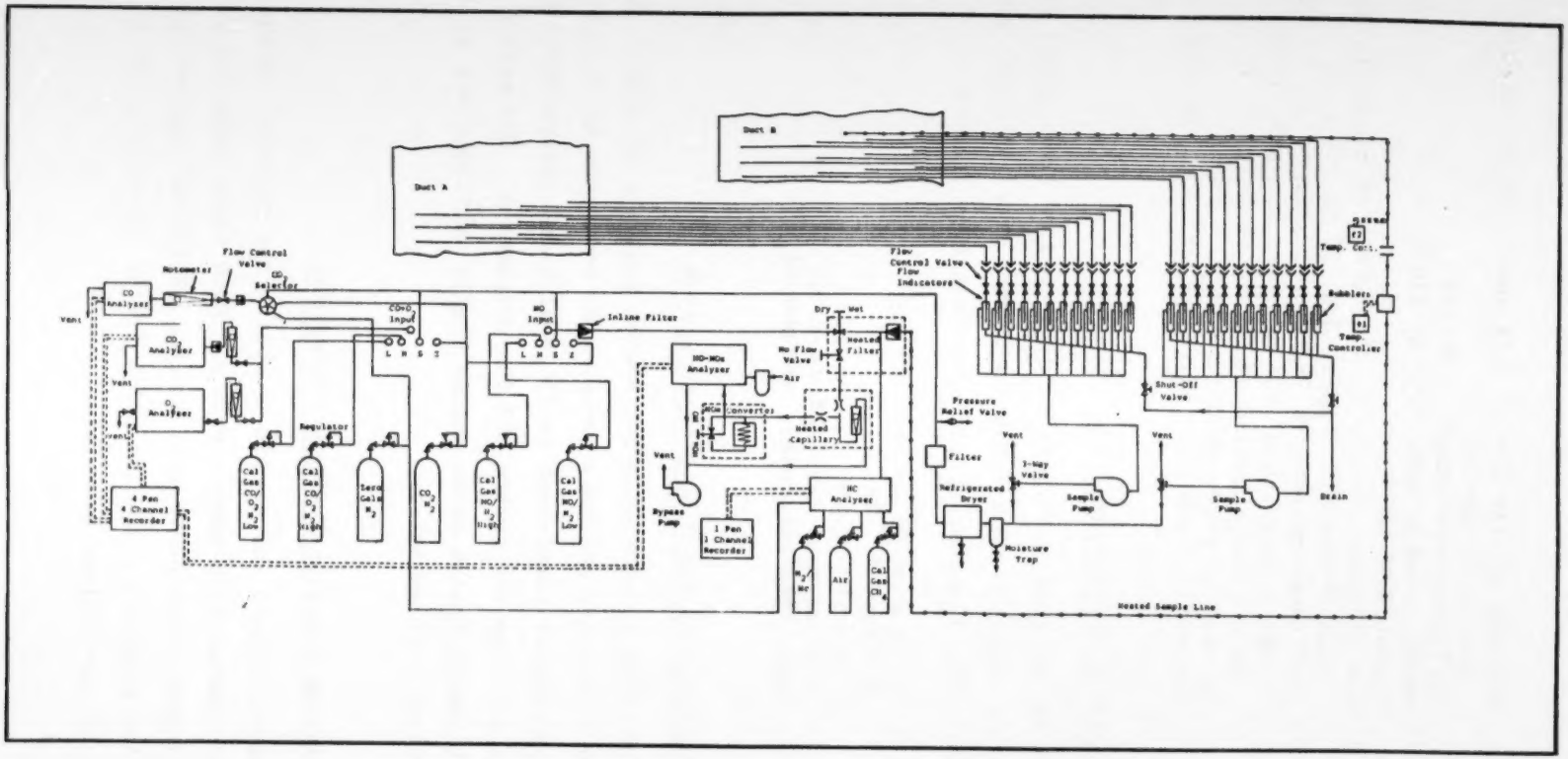



Figure 4-1. Flow Schematic of Mobile Flue Gas Monitoring Laboratory

Gas samples to be analyzed for $O_2$, $CO_2$, CO and NO are conveyed to the KVB mobile laboratory through 3/8 inch nylon sample lines. After passing through bubblers for flow control, the samples pass through a diaphragm pump and a refrigerated dryer to reduce the sample dew point temperature to 35°F. After the dryer, the sample gas is split between the various continuous gas monitors for analysis. Flow through each continuous monitor is accurately controlled with rotometers. Excess flow is vented to the outside. Gas samples may be drawn both individually and/or compositely from all probes during each test. The average emission values are reported in this report.

## 4.2 SULFUR OXIDES (SOx) MEASUREMENT AND PROCEDURES

Measurement of $SO_2$ and $SO_3$ concentrations is made by wet chemical analysis using both the "Shell-Emeryville" method and EPA Method 6. In the Shell-Emeryville method the gas sample is drawn from the stack through a glass probe (Figure 4-2), containing a quartz wool filter to remove particulate matter, into a system of three sintered glass plate absorbers (Figure 4-3). The first two absorbers contain aqueous isopropyl alcohol and remove the sulfur trioxide; the third contains aqueous hydrogen peroxide solution which absorbs the sulfur dioxide. Some of the sulfur trioxide is removed by the first absorber, while the remainder, which passes through as sulfuric acid mist, is completely removed by the secondary absorber mounted above the first. After the gas sample has passed through the absorbers, the gas train is purged with nitrogen to transfer sulfur dioxide, which has dissolved in the first two absorbers, to the third absorber to complete the separation of the two components. The isopropyl alcohol is used to inhibit the oxidation of sulfur dioxide to sulfur trioxide before it gets to the third absorber.

The isopropyl alcohol absorber solutions are combined and the sulfate resulting from the sulfur trioxide absorption is titrated with standard lead perchlorate solution using Sulfonazo III indicator. In a similar manner, the hydrogen peroxide solution is titrated for the sulfate resulting from the sulfur dioxide absorption.

The gas sample is drawn from the flue by a single probe made of quartz glass inserted into the duct approximately one-third to one-half way.

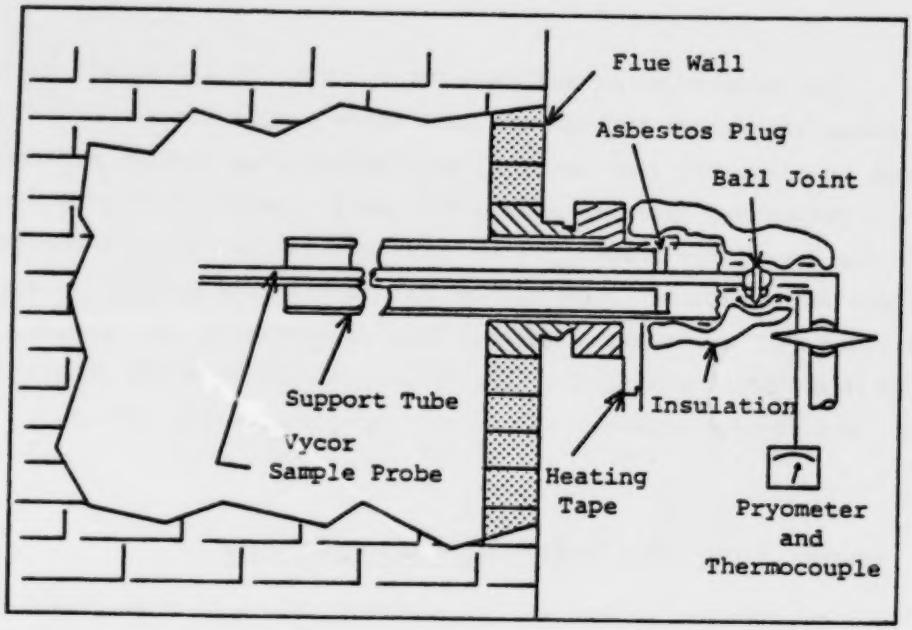



Figure 4-2. SOx Sample Probe Construction

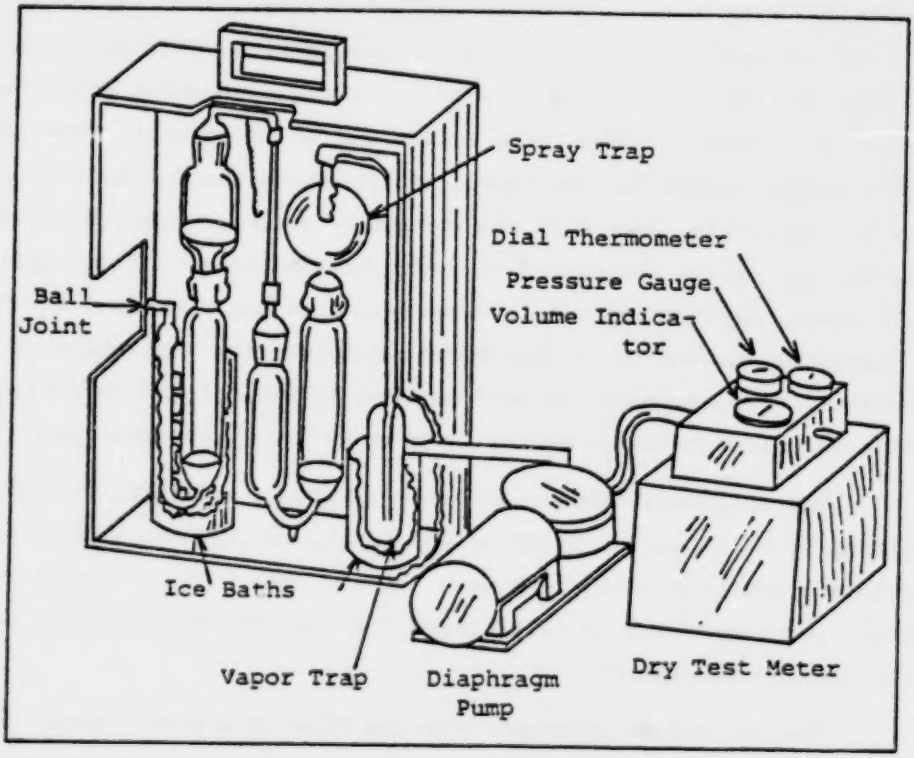



Figure 4-3. Sulfur Oxides Sampling Train

The inlet end of the probe holds a quartz wool filter to remove particulate matter. It is important that the entire probe temperature be kept above the dew point of sulfuric acid during sampling (minimum temperature of 260°C). This is accomplished by wrapping the probe with a heating tape.

EPA Method 6, which is an alternative method for determining $SO_2$ (Figure 4-4), employs an impinger train consisting of a bubbler and three midget impingers. The bubbler contains isopropanol. The first and second impingers contain aqueous hydrogen peroxide. The third impinger is left dry. The quartz probe and filter used in the Shell-Emeryville method is also used in Method 6.

Method 6 differs from Shell-Emeryville in that Method 6 requires that the sample rate be proportional to stack gas velocity. Method 6 also differs from Shell-Emeryville in that the sample train in Method 6 is purged with ambient air, instead of nitrogen. Sample recovery involves combining the solutions from the first and second impingers. A 10 ml aliquot of this solution is then titrated with standardized barium perchlorate.

Two repetitions of Shell-Emeryville and two repetitions of EPA Method 6 were made during each test.

## 4.3 PARTICULATE MEASUREMENT AND PROCEDURES

Particulate samples are taken at the same sample ports as the gaseous emission samples using a Joy Manufacturing Company portable effluent sampler (Figure 4-5). This system, which meets the EPA design specifications for Test Method 5, Determination of Particulate Emissions from Stationary Sources (Federal Register, Volume 36, No. 27, page 24888, December 23, 1971), is used to perform both the initial velocity traverse and the particulate sample collection. Dry particulates are collected in a heated case using first a cyclone to separate particles larger than five micrometers and a 100 mm glass fiber filter for retention of particles down to 0.3 micrometers. Condensible particulates are collected in a train of four Greenburg-Smith impingers in an ice water bath. The control unit includes a total gas meter and thermocouple indicator. A pitot tube system is provided for setting sample flows to obtain isokinetic sampling conditions.

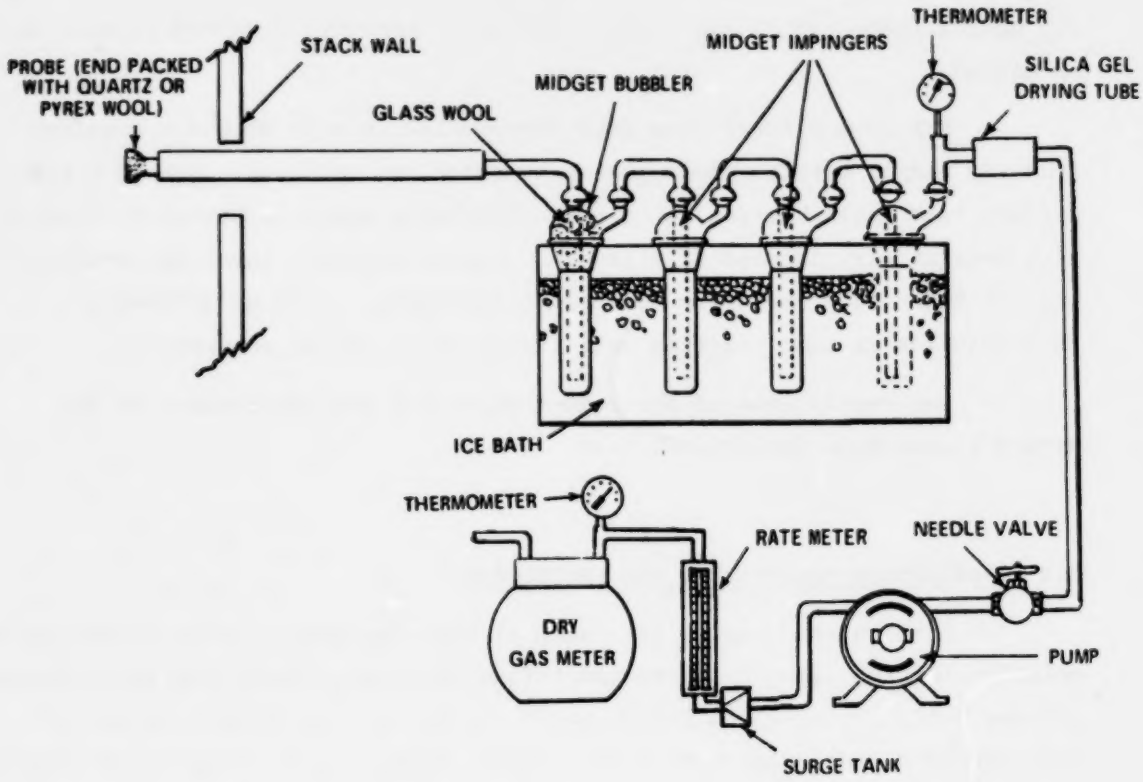



Figure 4-4. EPA Method 6 Sulfur Oxide Sampling Train

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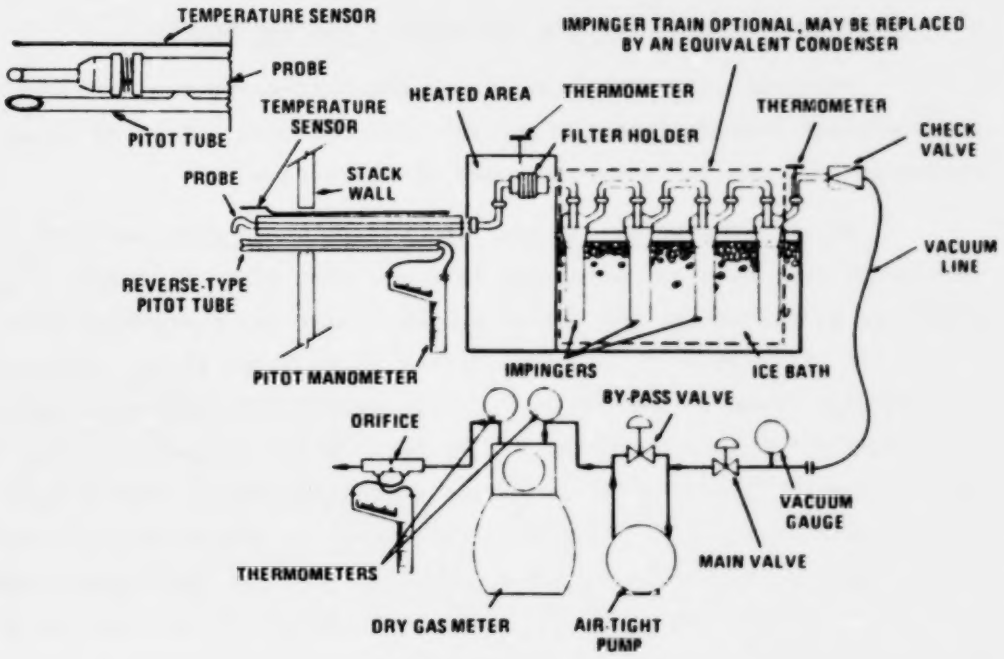


Figure 4-5. EPA Method 5 Particulate Sampling Train

All peripheral equipment is carried in the instrument van. This includes a scale (accurate to $\pm$0.1 mg), hot plate, drying oven (212°F), high temperature oven, desiccator, and related glassware. A particulate analysis laboratory is set up in the vicinity of the boiler in a vibration-free area. Here filters are prepared, tare weighed and weighed again after particulate collection. Also, probe washes are evaporated and weighed in the lab.

## 4.4 PARTICLE SIZE DISTRIBUTION MEASUREMENT AND PROCEDURE

Particle size distribution was measured using two methods. These are the Brink Cascade Impactor and the SASS cyclones. Each of these particle sizing methods has its advantages and disadvantages.

Brink. The Brink cascade impactor is an in situ particle sizing device which separates the particles into six size classifications. It has the advantage of collecting the entire sample. That is, everything down to the collection efficiency of the final filter is included in the analysis. It has, however, some disadvantages. If the particulate matter is spatially stratified within the duct, the single-point Brink sampler will yield erroneous results. Unfortunately, the particles at the outlets of stoker boilers may be considerably stratified. Another disadvantage is the instrument's small classification range (0.3 to 3.0 micrometers) and its small sample nozzle (1.5 to 2.0 mm maximum diameter). Both are inadequate for the job at hand. The particles being collected at the boiler outlet are often as large as the sample nozzle.

The sampling procedure is straight forward. First, the gas velocity at the sample point is determined using a calibrated S-type pitot tube. For this purpose a hand held particulate probe, inclined manometer, thermocouple and indicator are used. Second, a nozzle size is selected which will maintain isokinetic flow rates within the recommended .02 - .07 $ft^3$/min rate at stack conditions. Having selected a nozzle and determined the required flow rate for isokinetics, the operating pressure drop across the impactor is determined from a calibration curve. This pressure drop is corrected for temperature, pressure and molecular weight of the gas to be sampled.

A sample is drawn at the predetermined $\Delta P$ for a time period which is dictated by mass loading and size distribution. To minimize weighing errors, it is desirable to collect several milligrams on each stage. However, to minimize reentrainment, a rule of thumb is that no stage should be loaded above 10 mg. A schematic of the Brink sampling train is shown in Figure 4-6.

SASS. The Source Assessment Sampling System (SASS) was not designed principally as a particle sizer but it includes three calibrated cyclones which can be used as such. The SASS train is a single point in-situ sampler. Thus, it is on a par with cascade impactors. Because it is a high volume sampler and samples are drawn through large nozzles (0.25 to 1.0 in.), it has an advantage over the Brink cascade impactor where large particles are involved. The cut points of the three cyclones are 10, 3 and 1 micrometers. A detailed description of the SASS train is presented in Section 4.8.

## 4.5 COAL SAMPLING AND ANALYSIS PROCEDURE

Coal samples at Test Site J were taken during each test from the weigh lorry, as coal was being added to the boiler. The samples were processed and analyzed for both size consistency and chemical composition. This is close enough to the furnace that the coal sampled simultaneously with testing is representative of the coal fired during testing. In order to collect representative coal samples, ten pounds of coal were taken from each batch added from the weigh lorry.

The sampling procedure is as follows. At the start of testing one increment of sample is collected from the weigh lorry. This is repeated for each batch of coal added during the test (three to five hours duration) so that a 7 to 12 increment sample is obtained. The total sample is then riffled using a Gilson Model SP-2 Porta Splitter until two representative twenty-point samples are obtained.

The sample to be used for sieve analysis is air dried overnight. Drying of the coal is necessary for good separation of fines. If the coal is wet, fines cling to the larger pieces of coal and to each other. Once dry, the coal is sized using a six tray Gilson Model PS-3 Porta Screen. Screen

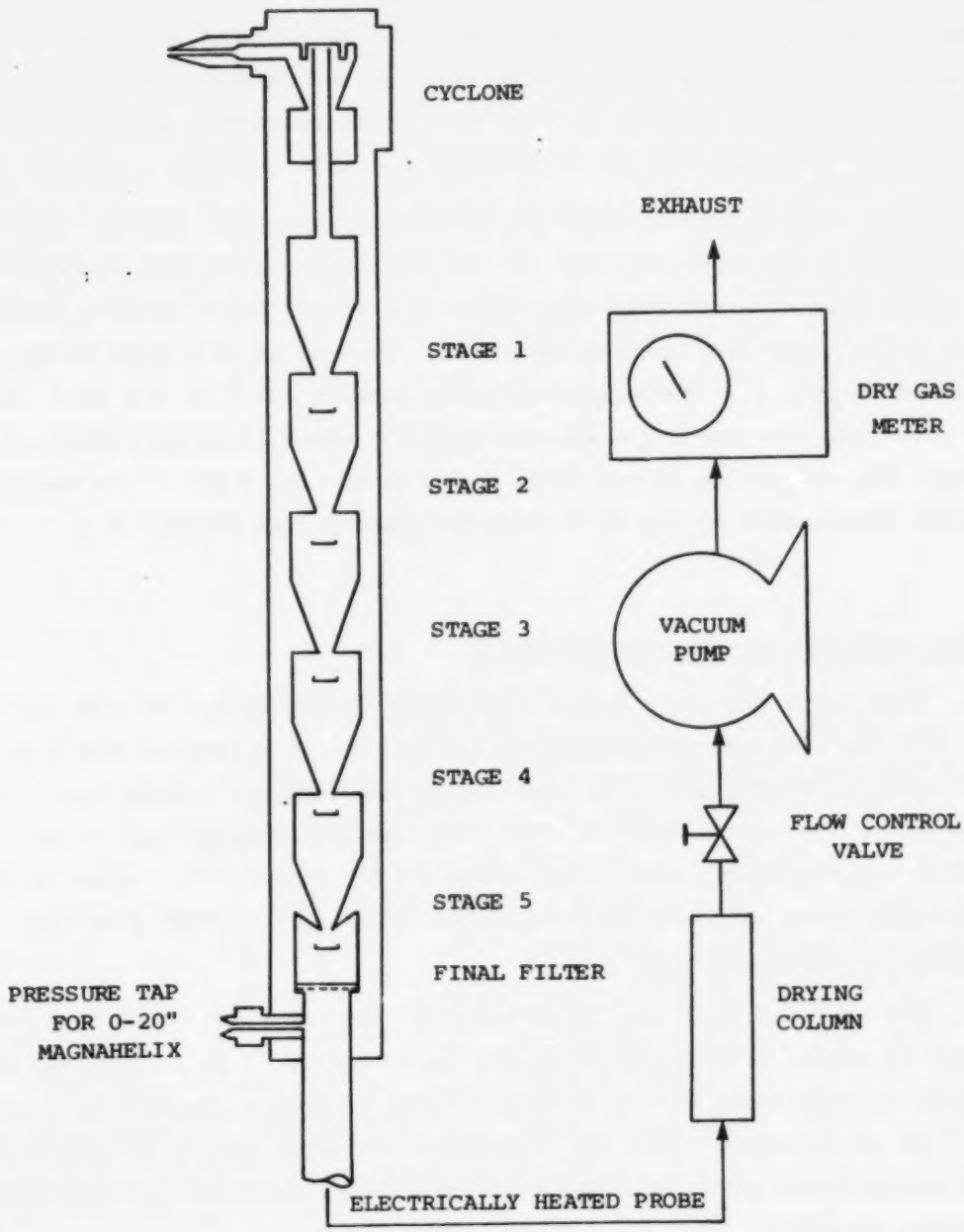


Figure 4-6. Brink Cascade Impactor Sampling Train Schematic

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sizes used are 1", 1/2", 1/4", #8 and #16 mesh. Screen area per tray is 14"x14". The coal in each tray is weighed on a triple beam balance to the nearest 0.1 gram.

The coal sample for chemical analysis is reduced to 2-3 pounds by further riffling and sealed in a plastic bag. All coal samples are sent to Commercial Testing and Engineering Company, South Holland, Illinois. Each sample associated with a particulate loading or particle sizing test is given a proximate analysis. In addition, composite samples consisting of one increment of coal for each test for each coal type receive ultimate analysis, ash fusion temperature, mineral analysis, Hardgrove grindability and free swelling index measurements.

## 4.6 ASH COLLECTION AND ANALYSIS FOR COMBUSTIBLES

The combustible content of flyash is determined in the field by KVB in accordance with ASTM D3173, "Moisture in the Analysis Sample of Coal and Coke" and ASTM D3174, "Ash in the Analysis Sample of Coal and Coke."

The flyash sample is collected by the EPA Method 5 particulate sample train while sampling for particulates. The cyclone catch is placed in a desiccated and tare-weighed ceramic crucible. The crucible with sample is heated in an oven at 230°F to remove its moisture. It is then desiccated to room temperature and weighed. The crucible with sample is then placed in an electric muffle furnace maintained at a temperature of 1400°F until ignition is complete and the sample has reached a constant weight. It is cooled in a desiccator over desiccant and weighed. Combustible content is calculated as the percent weight loss of the sample based on its post 230°F weight.

At Test Site J the bottom ash samples were collected in several increments from the ash pit after testing. These samples were mixed, quartered, and sent to Commercial Testing and Engineering Company for combustible determination. Multiclone ash samples were taken from ports near the base of the multiclone hopper. The sample, approximately two quarts in size, was sent to Commercial Testing and Engineering Company for combustible determination.

## 4.7 BOILER EFFICIENCY EVALUATION

Boiler efficiency is calculated using the ASME Test Form for Abbreviated Efficiency Test, Revised, September, 1965. The general approach to efficiency evaluation is based on the assessment of combustion losses. These losses can be grouped into three major categories: stack gas losses, combustible losses, and radiation losses. The first two groups of losses are measured directly. The third is estimated from the ABMA Standard Radiation Loss Chart.

Unlike the ASME test in which combustible losses are lumped into one category, combustible losses are calculated and reported separately for combustibles in the bottom ash, combustibles in the mechanically collected ash and combustibles in the flyash leaving the boiler.

## 4.8 TRACE SPECIES MEASUREMENT

The EPA (IERL-RTP) has developed the Source Assessment Sampling System (SASS) train for the collection of particulate and volatile matter in addition to gaseous samples (Figure 4-7). The "catch" from the SASS train is analyzed for polynuclear aromatic hydrocarbons (PAH) and inorganic trace elements.

In this system, a stainless steel heated probe is connected to an oven module containing three cyclones and a filter. Size fractionation is accomplished in the series cyclone portion of the SASS train, which incorporates the cyclones in series to provide large quantities of particulate matter which are classified by size into three ranges:

A) >10 μm B) 3 μm to 10 μm C) 1 μm to 3 μm

Together with a filter, a fourth cut (<1 μm) is obtained. Volatile organic material is collected in an XAD-2 sorbent trap. The XAD-2 trap is an integral part of the gas treatment system which follows the oven containing the cyclone system. The gas treatment system is composed of four primary components: the gas conditioner, the XAD-2 organic sorbent trap, the aqueous condensate collector, and a temperature controller. The XAD-2 sorbent is a porous poly-

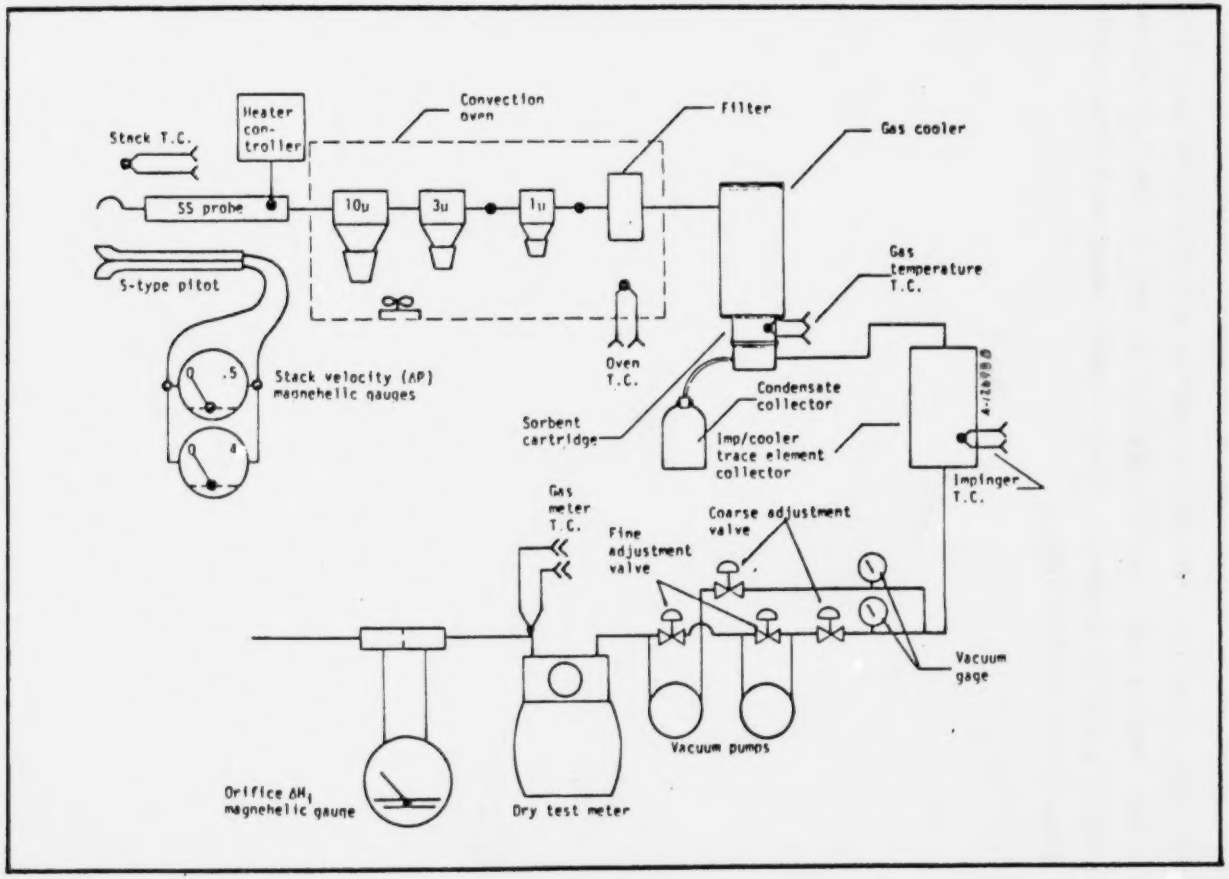


Figure 4-7. Source Assessment Sampling (SASS) Flow Diagram

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mer resin with the capability of absorbing a broad range of organic species. Some trapping of volatile inorganic species is also anticipated as a result of simple impaction. Volatile inorganic elements are collected in a series of impingers. The pumping capacity is supplied by two 10 cfm high volume vacuum pumps, while required pressure, temperature, power and flow conditions are obtained from a main controller.

# 5.0 TEST RESULTS AND OBSERVATIONS

This section presents the results of tests performed on Boiler J. Observations are made regarding the influence of the control parameters on stack emissions and on boiler efficiency. The control parameters examined include overfire air (OFA), excess air expressed in terms of excess oxygen, boiler load expressed in terms of grate heat release, and coal properties.

Sixteen tests were conducted over a one-month period to develop this data. Startup problems on the boiler and time constraints on the test crew prevented some of the desired data from being obtained. In addition, the carbon monoxide analyzer used by the test crew was out of service during these tests. Those tests successfully completed are outlined in Tables 2-1 and 2-2 of the Executive Summary. Discussion of the data follows.

## 5.1 OVERFIRE AIR

The overfire air (OFA) system on Boiler J consisted of a single row of jets on the front water wall three feet 10 inches above the grate. Air flow to these jets can be manually controlled by the operators who normally maintained low OFA pressures. The operators feel that low overfire air gives them better efficiency and less clinkering on the grate.

During the testing of this unit, tests were run at several different overfire air pressures. However, because of the previously mentioned startup problems and time constraints, several key tests were not completed. This makes the task of sorting out trends due to overfire air a difficult one at this site. Nevertheless, some trends are evident as described in the following discussions.

### 5.1.1 Particulate Loading vs Overfire Air

Particulate loading increased whenever overfire air increased, at constant load. This trend was true at both the boiler outlet and after the mechanical dust collector as shown in Figures 5-1 and 5-2.

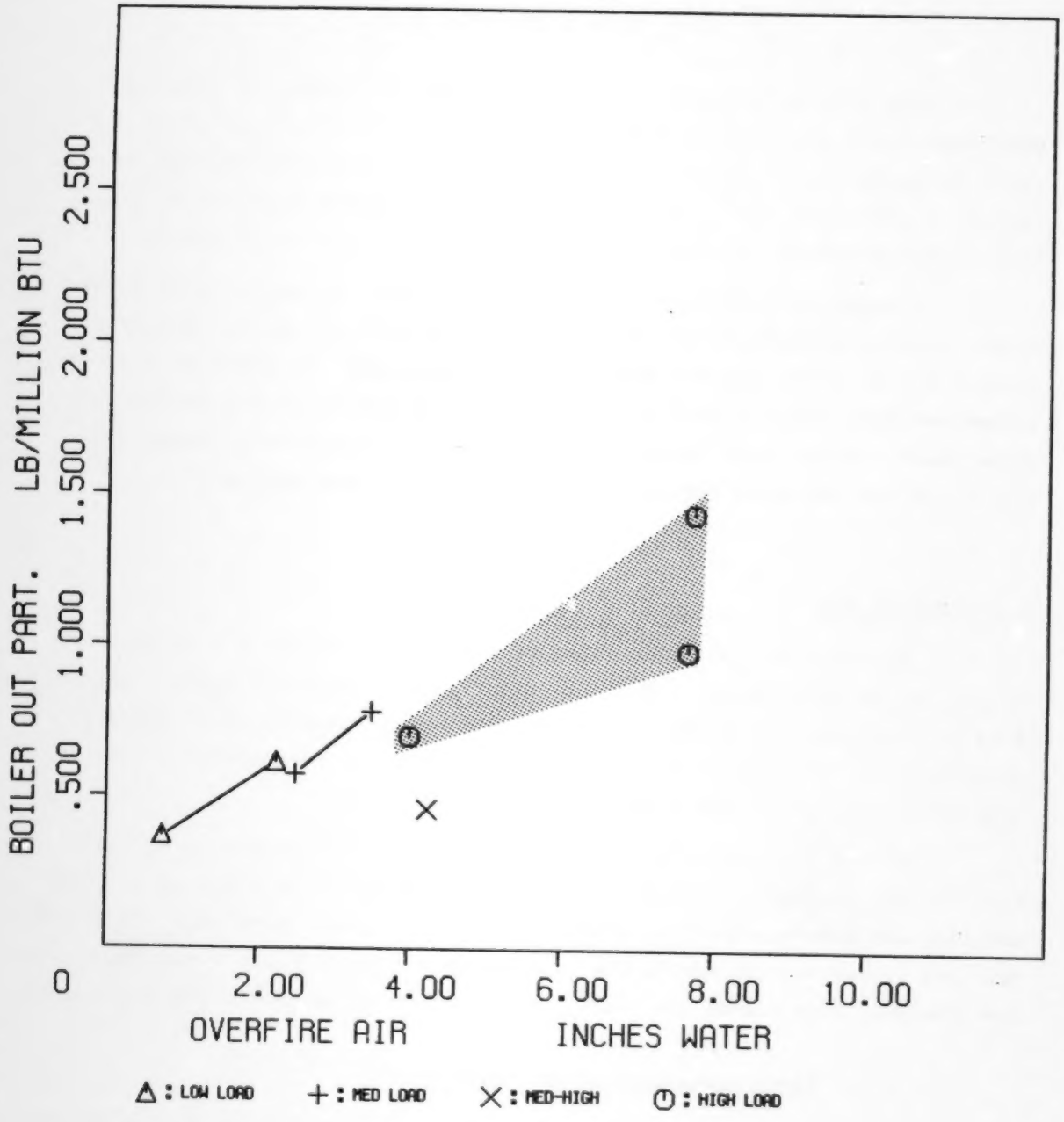


FIG. 5-1

BOILER OUT PART. VS. OVERFIRE AIR
TEST SITE J

4-15900-545

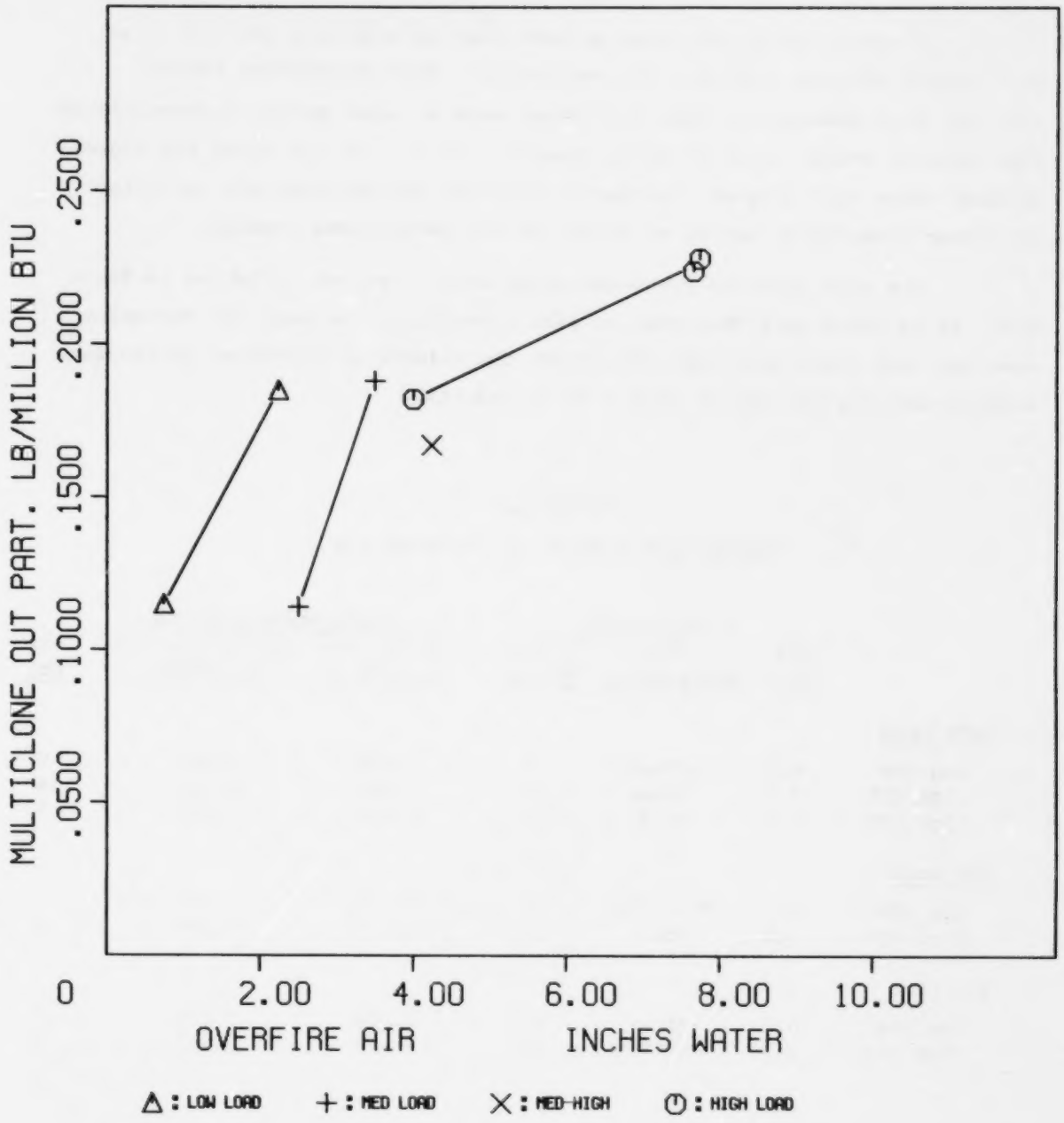


FIG. 5-2

MULTICLONE OUT PART. VS. OVERFIRE AIR
TEST SITE J

4-15900-545

However, it is important to note that in each case the coal fines were higher whenever overfire air was higher. This coincidence raises the very real possibility that coal fines were at least partly responsible for the observed change in particulate loading. In each of the other ten stokers studied under this program, increasing overfire air pressure had the effect of either reducing or having no effect on the particulate loading.

The test data are presented along with three key variables in Table 5-1. It is noted here that coal is also a variable. Because the variables coal and coal fines were not controlled, the relationship between particulate loading and overfire air at this site is undefined.

TABLE 5-1

PARTICULATE LOADING VS OVERFIRE AIR

| | VARIABLES | | | PARTICULATE LOADING | | |
|---|---|---|---|---|---|---|
| | OFA "$H_2O$ | Coal Designation | % Coal Fines | Boiler Out lb/$10^6$Btu | Multiclone Out lb/$10^6$Btu | Test No. |
| 100% Load | | | | | | |
| Low OFA | 4.0 | Kentucky | 5 | 0.699 | 0.182 | 6 |
| High OFA | 7.7 | Ohio | 11 | 0.984 | 0.224 | 14 |
| High OFA | 7.8 | Ohio | 37 | 1.442 | 0.228 | 5 |
| 75% Load | | | | | | |
| Low OFA | 2.5 | Kentucky | 11 | 0.574 | 0.114 | 8 |
| High OFA | 3.5 | Ohio | 18 | 0.779 | 0.188 | 2 |
| 50% Load | | | | | | |
| Low OFA | 0.8 | Ohio | 11 | 0.369 | 0.115 | 1 |
| High OFA | 2.3 | Kentucky | 18 | 0.617 | 0.185 | 9 |

### 5.1.2 Nitric Oxide vs Overfire Air

There is a general trend for nitric oxide to increase as overfire air increases on this unit. As with the particulate data, this statement must be qualified by noting that other variables are involved which could have influenced the data.

Data from four selected tests are presented in Table 5-2. These four tests were conducted under similar conditions of boiler load and excess oxygen, the two variables known to affect nitric oxide formation. The trend in nitric oxide concentration is apparent.

TABLE 5-2

NITRIC OXIDE VS OVERFIRE AIR

| TEST CONDITIONS | | | | | | |
|---|---|---|---|---|---|---|
| OFA "$H_2O$ | Load % | $O_2$ % | Coal | % Coal Fines | NO as $NO_2$ lb/$10^6$Btu | Test No. |
| 1.0 | 103 | 7.9 | Ohio | 18 | 0.282 | 13 |
| 4.0 | 99 | 8.1 | Ky | 5 | 0.337 | 6 |
| 5.8 | 94 | 7.9 | Ky | 5 | 0.322 | 15 |
| 7.8 | 103 | 7.9 | Ohio | 37 | 0.393 | 5 |

### 5.1.3 Boiler Efficiency vs Overfire Air

Boiler efficiency was observed to decrease by an average two percent when overfire air was increased. This decrease in efficiency was the combined result of increased dry gas losses and increased combustible losses. The observed change in efficiency may not be due solely to overfire air changes. Other variables not under our control could have been involved.

The average heat loss data for the full load Ohio coal tests is presented as a function of overfire air in Table 5-3.

TABLE 5-3

BOILER EFFICIENCY VS OVERFIRE AIR

| | HEAT LOSSES, % | | | | |
|---|---|---|---|---|---|
| | Dry Gas | Flyash Combustibles | Bottom Ash Combustibles | Other | % BOILER EFFICIENCY |
| Low OFA (Tests 7, 13) | 8.96 | 0.11 | 1.70 | 6.54 | 82.69 |
| High OFA (Tests 5, 14, 16) | 9.85 | 0.41 | 2.56 | 6.54 | 80.64 |

### 5.1.4 Overfire Air Flow Rate

The rate at which air is injected into the furnace above the grate was measured by traversing the overfire air supply duct with a standard pitot tube. This measurement was repeated at three overfire air flow rates corresponding to static pressures of 0.5, 2.5 and 8.5 "$H_2O$. The test data are presented in Table 5-4. The percentage of combustion air supplied by the overfire air jets is based on a calculated 120,000 lb/hr combustion air requirement at full load and 8% $O_2$.

TABLE 5-4

OVERFIRE AIR FLOW RATE

| Overfire Air Pressure, "$H_2O$ | Air Flow Rate lb/hr | % Combustion Air Supplied by OFA @ 8% $O_2$ and 100% Capacity |
|---|---|---|
| 0.5 | 3,535 | 3% |
| 2.5 | 7,021 | 6% |
| 8.5 | 11,931 | 10% |

Figure 5-3 relates the measured overfire air flow rates to static pressure in the overfire air duct. Bernoulli's equation for fluid flow through an orifice predicts a linear relationship between flow rate and the square root of the pressure drop. It is for this reason that the overfire air data is plotted against the square root of the static pressure. It is seen that the measured relationship is nearly linear.

## 5.2 EXCESS OXYGEN AND GRATE HEAT RELEASE

The boiler at Test Site J was tested for emissions and boiler efficiency at loads ranging from 50 to 100% of design capacity. Oxygen levels ranged from 7.5% to 12.2% in these tests. This section profiles the various emissions and the boiler efficiencies as a function of the variables oxygen and boiler load.

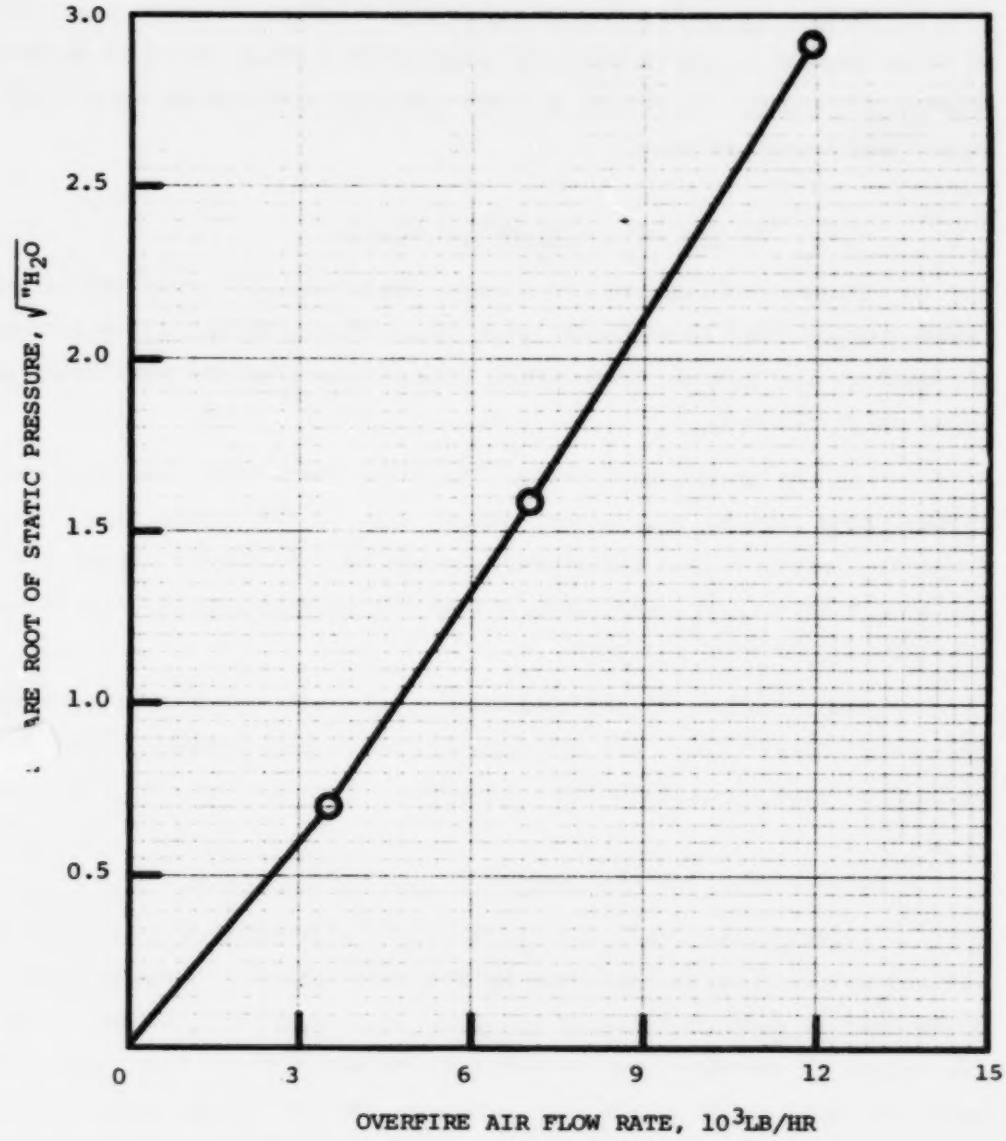


Figure 5-3. Relationship Between Overfire Air Flow Rate and Static Pressure Within the Overfire Air Duct - Test Site J.

Boiler steam loading is expressed in terms of grate heat release so as to provide a common basis of comparison between units of different sizes and designs. On Boiler J, 100% capacity corresponds to 350,000 Btu/hr-ft$^2$ grate heat release.

### 5.2.1 Excess Oxygen Operating Levels

Figure 5-4 depicts the various conditions of grate heat release and excess oxygen under which tests were conducted on Boiler J. Solid symbols are used to distinguish tests which included particulate mass loadings from those which did not.

At the design capacity of 70,000 lb steam/hour, the unit was operated in the range 7.5% to 9.1% excess oxygen (52% to 71% excess air). As the load dropped, the excess air requirement increased. At 75% of capacity 9.0-10.6% $O_2$ (70-95% excess air) was used, and at 50% of capacity 10.2-12.2% $O_2$ (84-129% excess air) was used.

These levels do not necessarily represent minimum or optimum conditions because a low air limit was not established. They represent the normal as-found operating conditions for this unit.

### 5.2.2 Particulate Loading vs Grate Heat Release

Particulate loadings were measured simultaneously at the boiler outlet and after the dust collector by EPA Test Method 5. The geometry of the boiler outlet duct on Boiler J was such that velocity readings in the lower two thirds of the duct were either null or negative in direction. As a result, only the upper third of the duct could be sampled for particulates. For this reason, the boiler outlet, or uncontrolled, particulate data should be considered suspect. The data presented may be considered an accurate measure of the particulate concentration in the upper third of the duct only. The dust collector outlet, or controlled, particulate data does not have this restriction and may be considered fully reliable.

The boiler outlet, or uncontrolled, particulate data is presented in Figure 5-5 as a function of grate heat release. Although suspect, the data is in the expected range for a mass fired traveling grate stoker. At

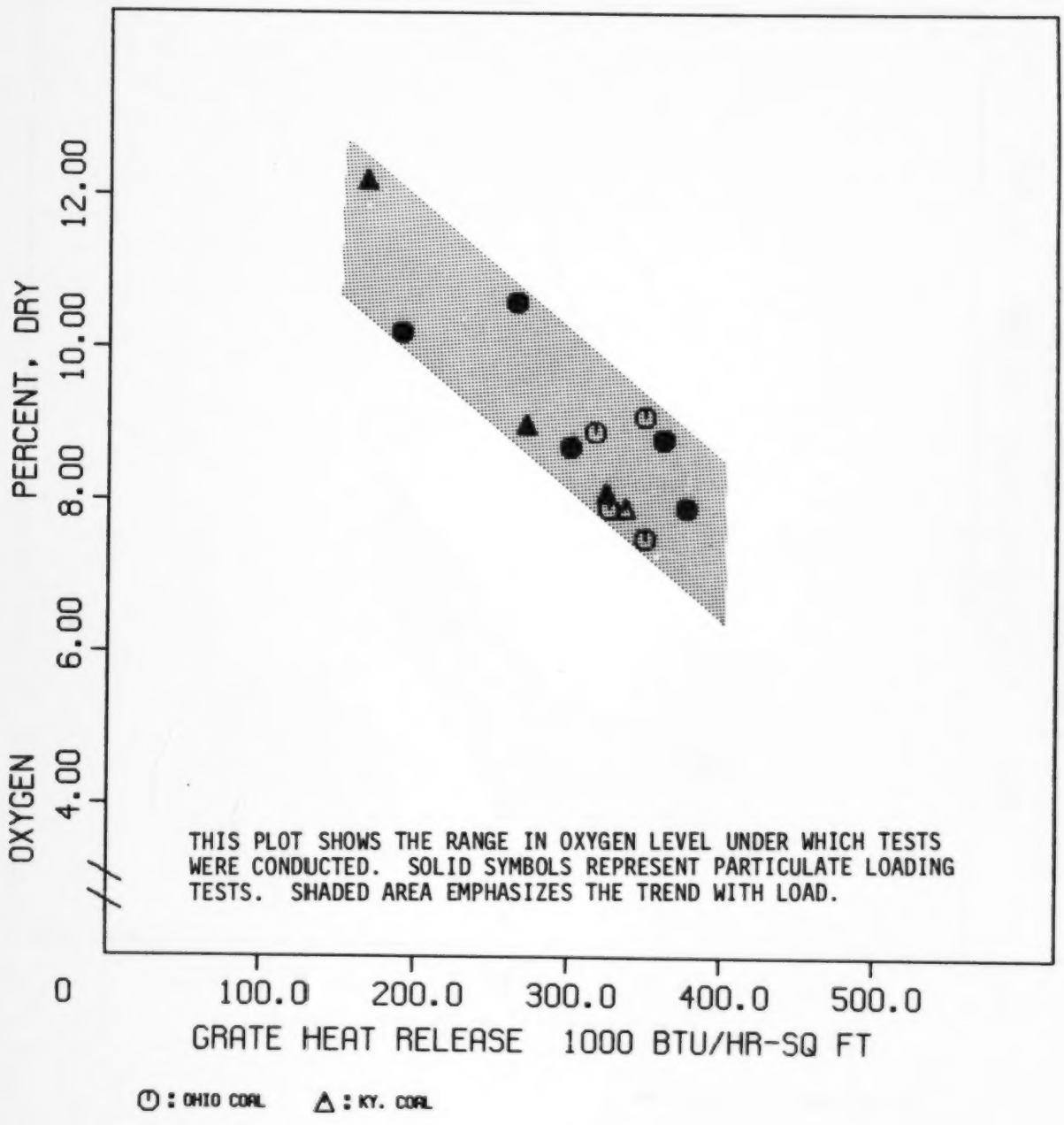


FIG. 5-4

OXYGEN VS. GRATE HEAT RELEASE

TEST SITE J

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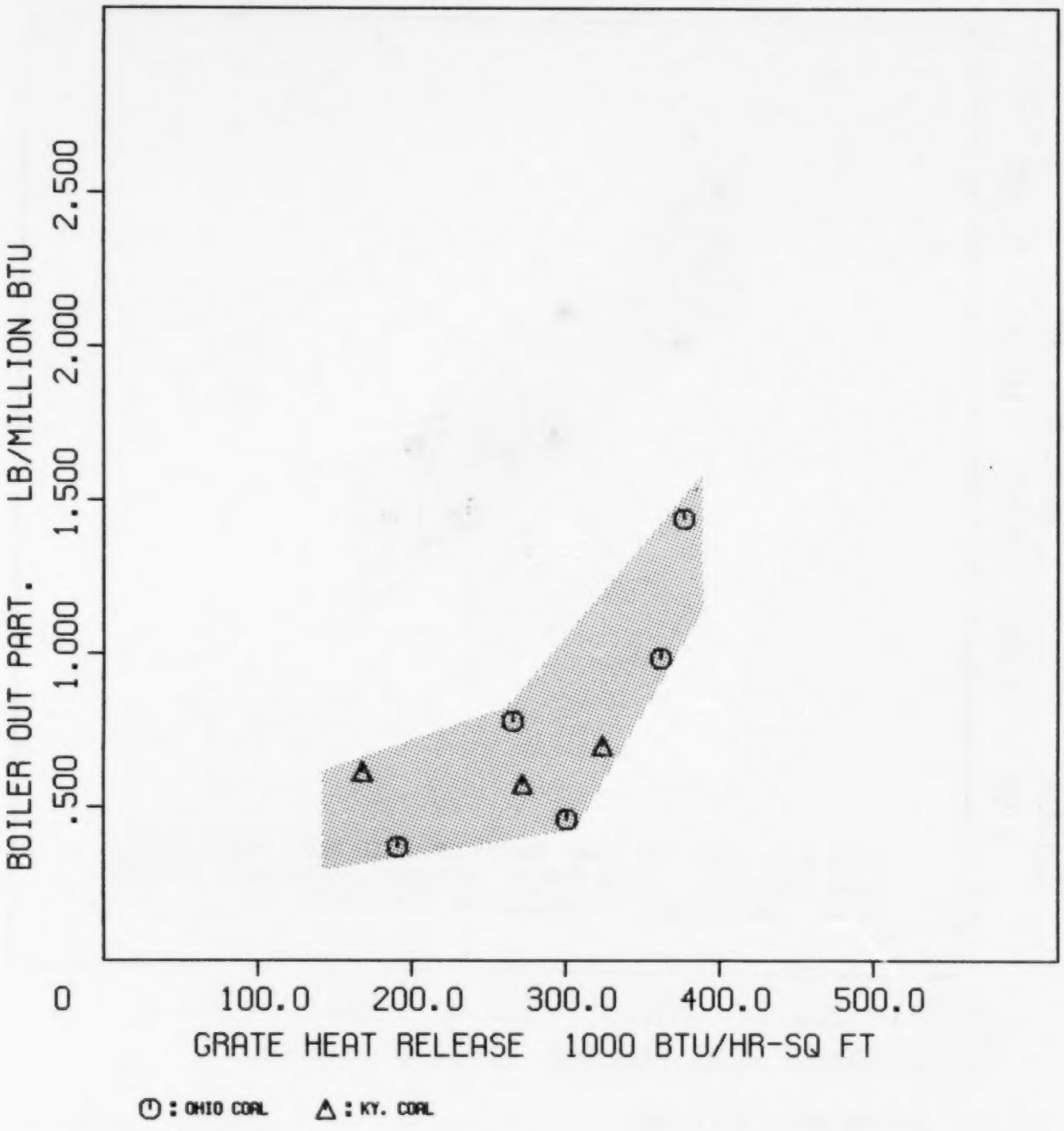


FIG. 5-5
BOILER OUT PART. VS. GRATE HEAT RELEASE
TEST SITE J

4-15900-545

full load, the particulate loading ranges from a low of 0.70 lb/$10^6$Btu to a high of 1.44 lb/$10^6$Btu. This loading drops off at lower loads.

Figure 5-6 presents the dust collector outlet particulate loading as measured at the stack. This data, assumed to be entirely accurate, also shows an increase in particulate loading with increasing load. At full load, the particulate loading ranges from 0.182 to 0.228 lb/$10^6$Btu, and drops to as low as 0.114 lb/$10^6$Btu at lower loads.

Ash carryover was determined for several tests by comparing the ash content of the uncontrolled flyash with the ash content of the coal. The average ash carryover for this unit was 10%. The data is presented in Table 5-5.

TABLE 5-5

ASH CARRYOVER

| Test No. | FIRING CONDITIONS Load % | $O_2$ % | OFA "$H_2O$ | Coal | Ash in Coal lb/$10^6$Btu | Ash in Flyash lb/$10^6$Btu | % Ash Carryover |
|---|---|---|---|---|---|---|---|
| 5 | 103 | 7.9 | 7.8 | Ohio | 8.13 | 1.100 | 13.5 |
| 7 | 85 | 8.7 | 4.3 | Ohio | 5.32 | 0.348 | 6.5 |
| 2 | 74 | 10.6 | 3.5 | Ohio | 5.27 | 0.585 | 11.1 |
| 1 | 48 | 10.2 | 0.8 | Ohio | 4.65 | 0.270 | 5.8 |
| 6 | 99 | 8.1 | 4.0 | Ky | 2.99 | 0.512 | 17.1 |
| 8 | 73 | 9.0 | 2.5 | Ky | 3.79 | 0.367 | 9.7 |
| 9 | 50 | 12.2 | 2.3 | Ky | 9.40 | 0.431 | 4.6 |
| | | | | | | Average | 9.8% |

### 5.2.3 Nitric Oxide vs Grate Heat Release and Oxygen

A total of thirteen nitric oxide data points were obtained under various operating conditions. This data is plotted as a function of grate heat release in Figure 5-7, and as a function of oxygen in Figure 5-8.

The data forms the expected trends with oxygen and load even though it is somewhat diffuse due to the many uncontrolled variables during testing. The

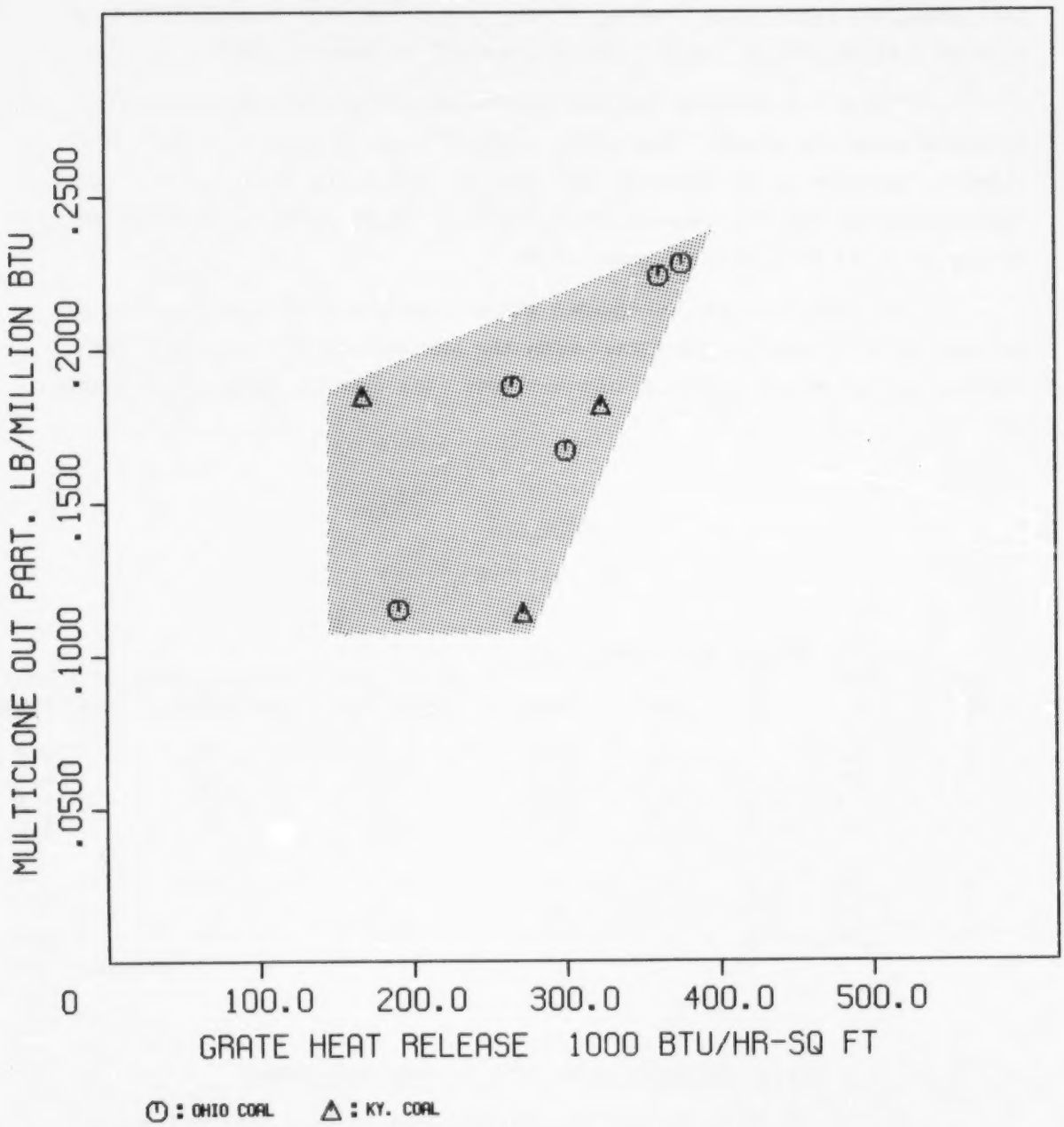


FIG. 5-6
MULTICLONE OUT PART. VS. GRATE HEAT RELEASE
TEST SITE J

4-15900-545

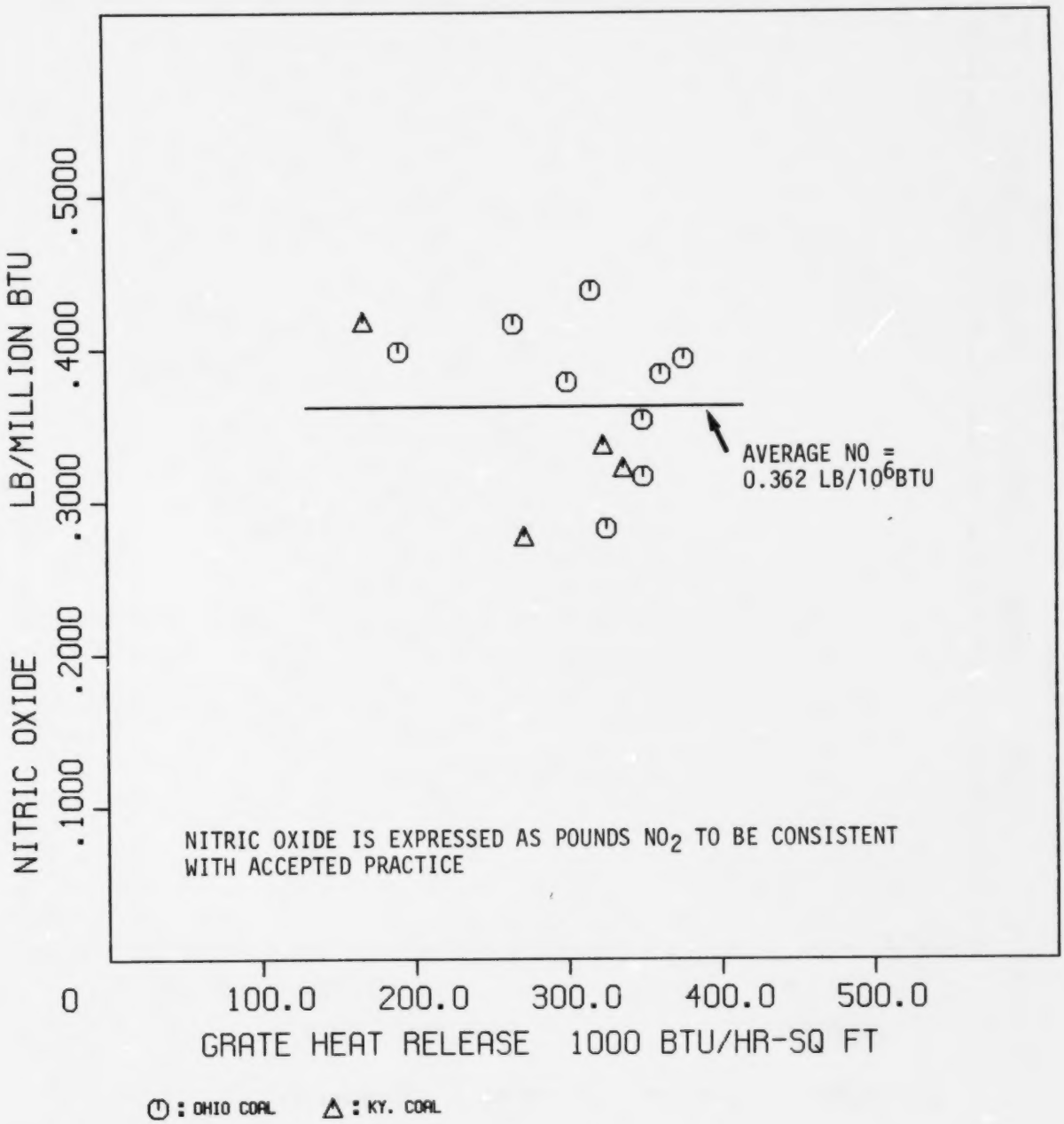


FIG. 5-7
NITRIC OXIDE VS. GRATE HEAT RELEASE
TEST SITE J

4-15900-545

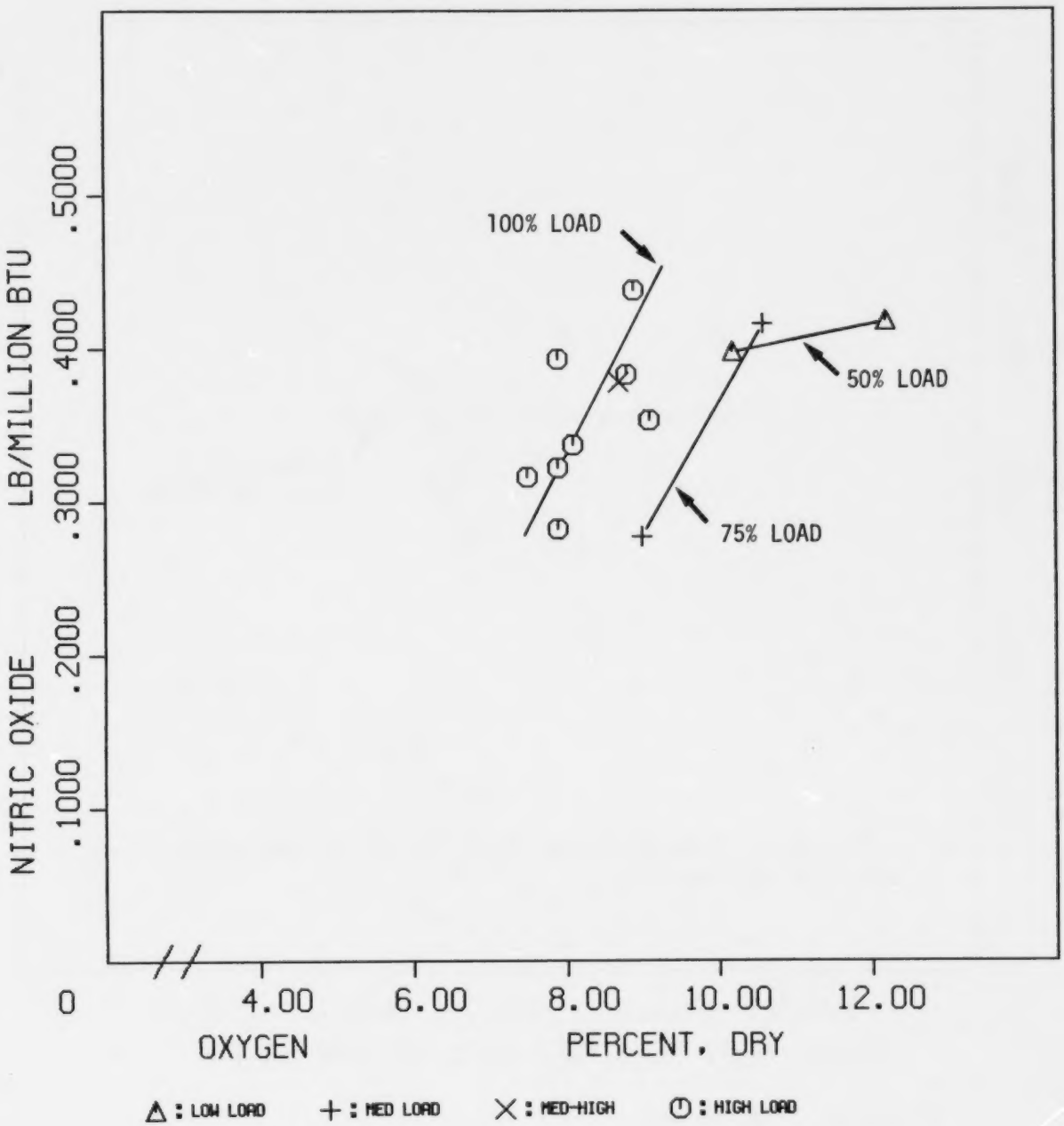


FIG. 5-8
NITRIC OXIDE VS. OXYGEN
TEST SITE J

4-15900-545

nitric oxide concentration increases with increasing oxygen with a slope of approximately 0.096 lb NO/$10^6$Btu/% $O_2$ as determined by linear regression analysis of the eight full load tests. At constant $O_2$, nitric oxide concentration increases with increasing load. The average nitric oxide concentration on this unit was 0.362 $\pm$.052 lb/$10^6$Btu expressed as $NO_2$.

### 5.2.4 Combustibles in the Ash vs Grate Heat Release

The combustible fraction of the boiler outlet flyash and bottom ash was determined for several ash samples corresponding to the particulate and SASS tests. The test data are plotted as a function of grate heat release in Figures 5-9 and 5-10. See discussion of combustibles vs size in Appendix E.

The average combustible content of the boiler outlet flyash samples was 27.6%. This combustible level was relatively constant with load, but appeared to be slightly higher for the Kentucky coal than for the Ohio coal, i.e., 31% vs 25%, respectively.

The average combustible content of the bottom ash samples was 20.6%. Here, the combustible level appears to increase somewhat with load as shown in Figure 5-10. Both coals had similar combustible levels.

### 5.2.5 Boiler Efficiency vs Grate Heat Release

Boiler efficiency was determined by the heat loss method for eleven of the tests. The boiler efficiency data are plotted as a function of grate heat release in Figure 5-11.

The drop in efficiency due to overfire air increases is very noticeable in this figure. The high overfire air test data, indicated by solid symbols, averaged two percent lower than the low overfire test data. This relationship was mentioned previously in Section 5.1.3, Boiler Efficiency vs Overfire Air.

Boiler efficiency averages 81.6% overall, with four low overfire air tests indicating efficiencies in the range 82.6% to 83.5%. Boiler efficiency decreases with load, as shown in Table 5-6. This decrease is primarily due to the increased dry gas loss.

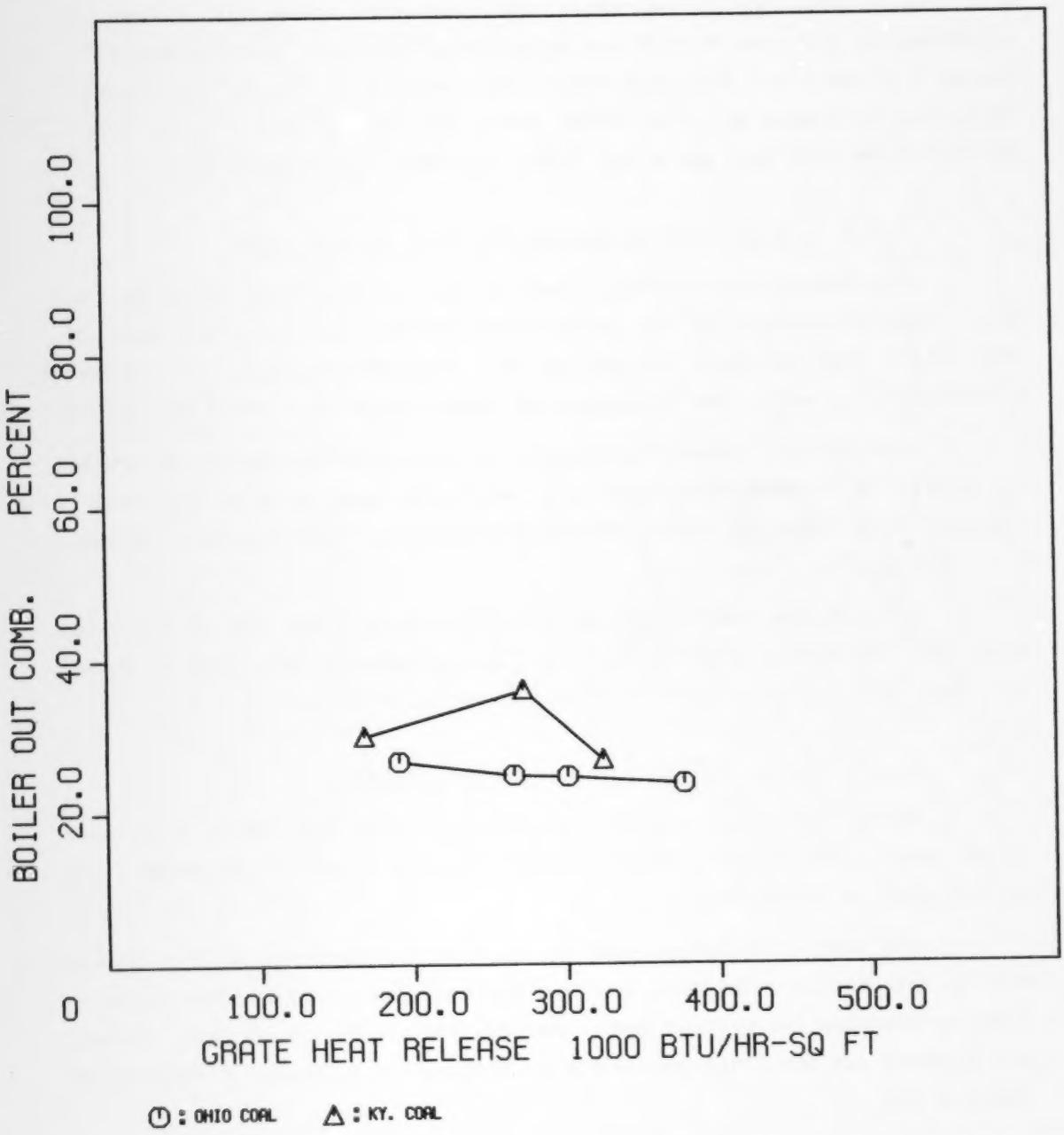


FIG. 5-9
BOILER OUT COMB. VS. GRATE HEAT RELEASE
TEST SITE J

4-15900-545

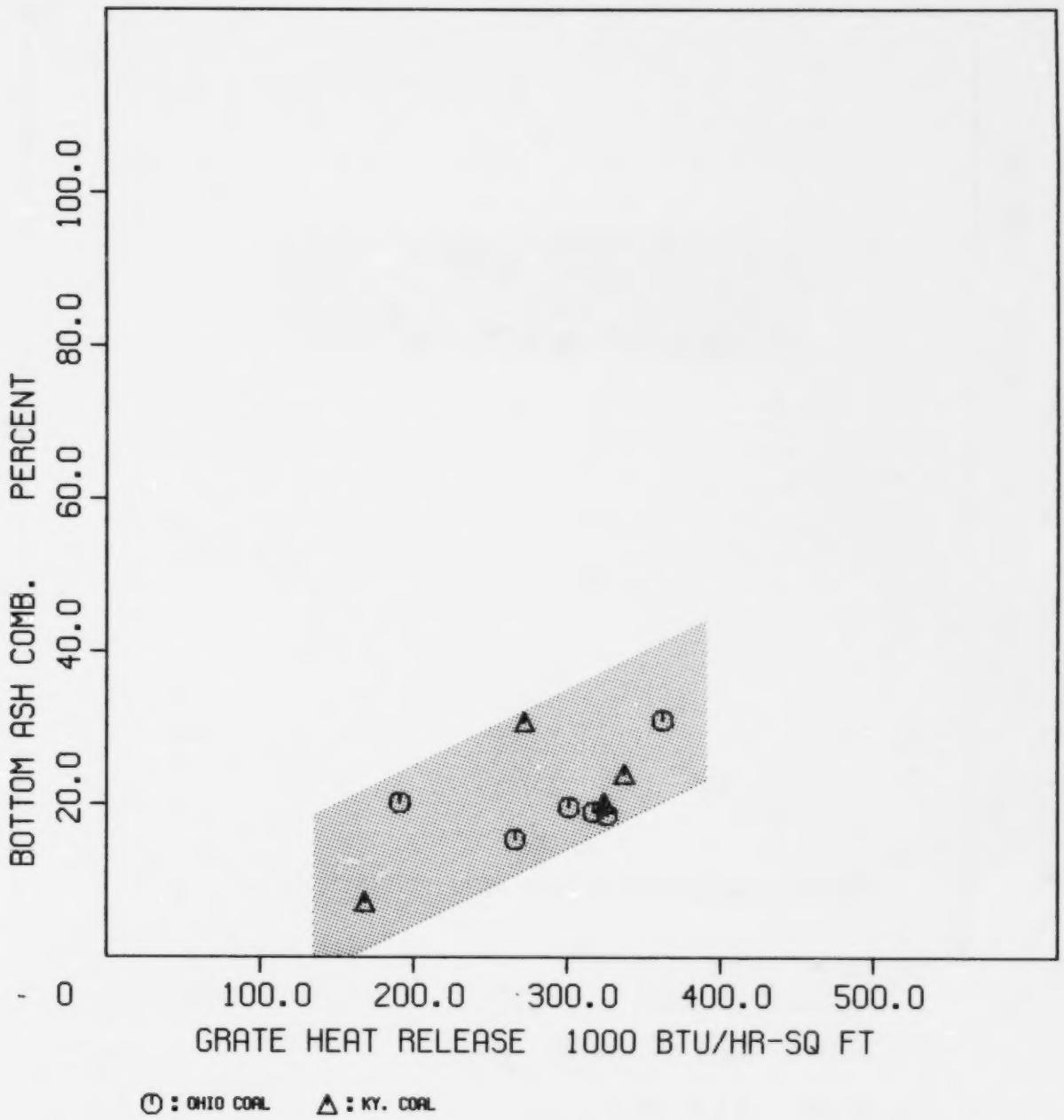


FIG. 5-10

BOTTOM ASH COMB. VS. GRATE HEAT RELEASE
TEST SITE J

4-15900-545

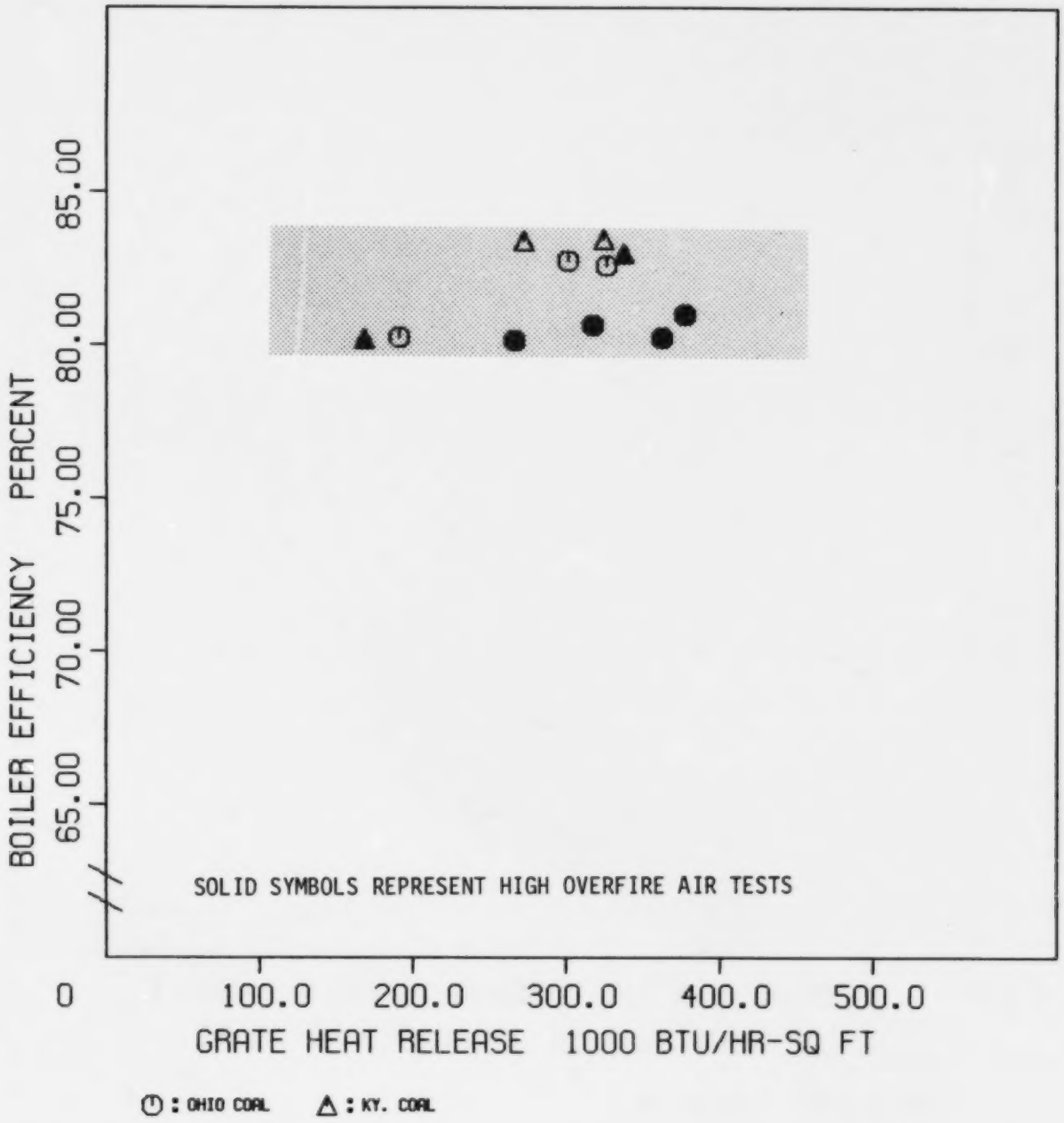


FIG. 5-11
BOILER EFFICIENCY VS. GRATE HEAT RELEASE
TEST SITE J

4-15900-545

TABLE 5-6

BOILER EFFICIENCY VS LOAD

| | AVERAGE HEAT LOSSES, % | | | | BOILER EFFICIENCY, % |
|---|---|---|---|---|---|
| | Dry Gas | Combustible | Radiation | Other | |
| 100% Load | 9.37 | 2.26 | 0.57 | 5.84 | 81.96 |
| 75% Load | 9.88 | 1.98 | 0.73 | 5.65 | 81.76 |
| 50% Load | 11.37 | 1.49 | 1.09 | 5.82 | 80.23 |

## 5.3 COAL PROPERTIES

Two coals were tested in Boiler J. These coals are identified in this report as Ohio coal and Kentucky coal. This section discusses the chemical and physical properties of these two coals, and discusses their observed influence on boiler emissions and efficiency.

### 5.3.1 Chemical Composition of the Coals

Representative coal samples were obtained during each particulate and SASS test. From each sample, a proximate analysis was obtained. Composite coal samples, containing portions of each individual sample, were also collected for each coal. The composite samples were given complete coal analysis including proximate, ultimate, ash fusion and minerals in the ash.

The moisture, ash and sulfur content of the two coals are compared on a heating value basis in Table 5-7. Such a comparison is often more meaningful than percentage by weight. This table shows the Kentucky coal to be the better coal in terms of its lower moisture, ash and sulfur, and its higher heating value.

The coal analysis for each individual sample are tabulated in Tables 5-8, 5-9, and 5-10.

TABLE 5-8

FUEL ANALYSIS - OHIO COAL
TEST SITE J

| TEST NO. | 01 | 02 | 05 | 07 | 13 | 14 | 16 | COMP | AVG | STD DEV |
|---|---|---|---|---|---|---|---|---|---|---|
| PROXIMATE (As Rec) | | | | | | | | | | |
| % Moisture | 2.89 | 3.12 | 4.44 | 2.93 | 4.85 | 3.18 | 3.73 | 3.05 | 3.59 | 0.78 |
| % Ash | 6.31 | 7.06 | 10.22 | 7.11 | 8.23 | 8.23 | 7.77 | 7.05 | 7.85 | 1.26 |
| % Volatile | 37.43 | 37.62 | 37.19 | 38.89 | 36.71 | 38.91 | 38.06 | 37.93 | 37.83 | 0.84 |
| % Fixed Carbon | 53.37 | 52.20 | 48.15 | 51.07 | 50.21 | 49.68 | 50.44 | 51.97 | 50.73 | 1.70 |
| Btu/lb | 13572 | 13405 | 12570 | 13373 | 12810 | 13101 | 12990 | 13368 | 13117 | 357 |
| % Sulfur | 1.06 | 1.52 | 2.18 | 1.68 | 1.64 | 1.82 | 2.02 | 1.75 | 1.70 | 0.36 |
| ULTIMATE (As Rec) | | | | | | | | | | |
| % Moisture | | | | | | | | 3.05 | | |
| % Carbon | | | | | | | | 74.74 | | |
| % Hydrogen | | | | | | | | 5.13 | | |
| % Nitrogen | | | | | | | | 1.66 | | |
| % Chlorine | | | | | | | | 0.19 | | |
| % Sulfur | | | | | | | | 1.75 | | |
| % Ash | | | | | | | | 7.05 | | |
| % Oxygen (diff) | | | | | | | | 6.43 | | |
| ASH FUSION (Red) | | | | | | | | | | |
| Initial Deformation | | | | | | | | 2100°F | | |
| Soft (H=W) | | | | | | | | 2250°F | | |
| Soft (H=1/2W) | | | | | | | | 2400°F | | |
| Fluid | | | | | | | | 2535°F | | |
| HARDGROVE GRINDABILITY | | | | | | | | 53 | | |
| FREE SWELLING INDEX | | | | | | | | 4 | | |
| % EQUILIBRIUM MOISTURE | | | | | | | | 2.94 | | |

TABLE 5-9

FUEL ANALYSIS - KENTUCKY COAL
TEST SITE J

| TEST NO. | 06 | 08 | 09 | 15 | COMP | AVG | STD DEV |
|---|---|---|---|---|---|---|---|
| PROXIMATE (As Rec) | | | | | | | |
| % Moisture | 2.02 | 1.94 | 2.91 | 2.09 | 1.96 | 2.24 | 0.45 |
| % Ash | 4.18 | 5.31 | 11.76 | 5.02 | 6.14 | 6.57 | 3.49 |
| % Volatile | 40.58 | 40.35 | 35.85 | 39.58 | 39.08 | 39.09 | 2.20 |
| % Fixed Carbon | 53.22 | 52.40 | 49.48 | 53.31 | 52.82 | 52.10 | 1.80 |
| Btu/lb | 13966 | 13995 | 12511 | 13954 | 13624 | 13607 | 731 |
| % Sulfur | 1.30 | 1.40 | 2.57 | 1.03 | 1.43 | 1.58 | 0.68 |
| ULTIMATE (As Rec) | | | | | | | |
| % Moisture | | | | | 1.96 | | |
| % Carbon | | | | | 76.77 | | |
| % Hydrogen | | | | | 5.09 | | |
| % Nitrogen | | | | | 1.23 | | |
| % Chlorine | | | | | 0.13 | | |
| % Sulfur | | | | | 1.43 | | |
| % Oxygen (diff) | | | | | 7.25 | | |
| % Ash | | | | | 6.14 | | |
| ASH FUSION (Red) | | | | | | | |
| Initial Deformation | | | | | 2205°F | | |
| Soft (H=W) | | | | | 2335°F | | |
| Soft (H=1/2W) | | | | | 2465°F | | |
| Fluid | | | | | 2580°F | | |
| % EQUILIBRIUM MOISTURE | | | | | 2.07 | | |
| HARDGROVE GRINDABILITY | | | | | 49 | | |
| FREE SWELLING INDEX | | | | | 6 | | |

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TABLE 5-10

MINERAL ANALYSIS OF COAL ASH
TEST SITE J

| Coal | Ohio | Ohio | Ky | Ky |
|---|---|---|---|---|
| Test No. | 16 | Comp | 15 | Comp |
| Silica | -- | 42.48 | -- | 44.08 |
| Alumina | -- | 26.60 | -- | 26.46 |
| Titania | -- | 1.29 | -- | 1.51 |
| Ferric Oxide | -- | 22.09 | -- | 17.80 |
| Lime | -- | 2.11 | -- | 2.28 |
| Magnesia | -- | 0.83 | -- | 0.78 |
| Potassium Oxide | -- | 1.91 | -- | 1.78 |
| Sodium Oxide | -- | 0.35 | -- | 0.80 |
| Sulfur Trioxide | -- | 1.43 | -- | 1.85 |
| Phos. Pentoxide | -- | 0.40 | -- | 0.31 |
| Undetermined | -- | 0.38 | -- | 1.89 |
| Silica Value | -- | 62.92 | -- | 67.88 |
| Base: Acid Ratio | -- | 0.39 | -- | 0.33 |
| $T_{250}$ Temperature | -- | 2425°F | -- | 2515°F |
| % Pyritic Sulfur | 1.39 | 0.97 | 0.26 | 0.68 |
| % Sulfate Sulfur | 0.10 | 0.05 | 0.02 | 0.02 |
| % Organic Sulfur | 0.53 | 0.73 | 0.75 | 0.73 |

TABLE 5-7

COAL PROPERTIES CORRECTED TO A CONSTANT $10^6$ BTU BASIS

| | Ohio Coal | Kentucky Coal |
|---|---|---|
| Moisture, lb/$10^6$Btu | 2.7 | 1.6 |
| Ash, lb/$10^6$Btu | 6.0 | 4.8 |
| Sulfur, lb/$10^6$Btu | 1.3 | 1.2 |
| Heating Value, Btu/lb | 13,117 | 13,607 |

### 5.3.2 Coal Size Consistency

Coal size consistency was determined for each coal sample obtained at Site J. The individual coal samples were screened at the site using 1", 1/2", 1/4", #8 and #16 square mesh screens. The results of these screenings are presented in Table 5-11. It is noted that the Kentucky coal, which was considered the better coal in terms of moisture, ash, sulfur and heating value, averaged slightly lower fines than the Ohio coal.

The coal size consistency measurements are presented on a statistical basis in Figures 5-12 and 5-13. Here, the standard deviation of the coal size consistency measurements are compared with the ABMA recommended limits for overfeed stokers. Both coals are sized on the low fines side of the ABMA recommended limits for overfeed stokers. This sizing is considered acceptable and should have no undesirable effects on the emissions.

### 5.3.3 Effect of Coal Properties on Emissions and Efficiency

The following discussion examines how emissions changed, or did not change, when coal was the variable. Frequent references are made to Figures in Section 5.2, Excess Oxygen and Grate Heat Release, which illustrate the relationships.

Excess Oxygen Operating Conditions. Figure 5-4 shows that several tests with each coal were run under similar oxygen load conditions and may be used for comparitive purposes. These include Tests 6 and 15 for Kentucky coal and Tests 3, 5 and 13 for Ohio coal. Also, Ohio coal Test 7 and Kentucky coal Test 8 are similar enough for comparative purposes.

TABLE 5-11

AS FIRED COAL SIZE CONSISTENCY

| Test No. | PERCENT PASSING STATED SCREEN SIZE 1" | 1/2" | 1/4" | #8 | #16 |
|---|---|---|---|---|---|
| 1 | 77.5 | 35.8 | 10.8 | 5.2 | 4.4 |
| 2 | 83.5 | 45.0 | 17.9 | 8.3 | 5.8 |
| 5 | 94.2 | 67.3 | 37.0 | 19.2 | 11.5 |
| 7 | 77.2 | 23.8 | 7.4 | 3.9 | 3.3 |
| 13 | 89.5 | 42.8 | 18.4 | 13.2 | 9.9 |
| 14 | 84.4 | 35.2 | 10.9 | 6.7 | 5.3 |
| 16 | 81.0 | 37.5 | 19.8 | 11.6 | 8.2 |
| Comp | 84.9 | 43.5 | 19.7 | 11.6 | 8.6 |
| Ohio Coal Average* | 83.9 | 41.1 | 17.5 | 9.7 | 6.9 |
| 6 | 90.6 | 20.8 | 4.8 | 3.3 | 2.9 |
| 8 | 97.0 | 44.6 | 10.9 | 5.1 | 4.2 |
| 9 | 94.0 | 53.1 | 18.0 | 9.5 | 7.4 |
| 15 | 94.0 | 23.9 | 4.8 | 3.3 | 3.0 |
| Comp | 94.5 | 34.3 | 10.1 | 5.7 | 4.5 |
| Kentucky Coal Average* | 93.9 | 35.6 | 9.6 | 5.3 | 4.4 |

*Data from Composite Samples are not Included in Averages

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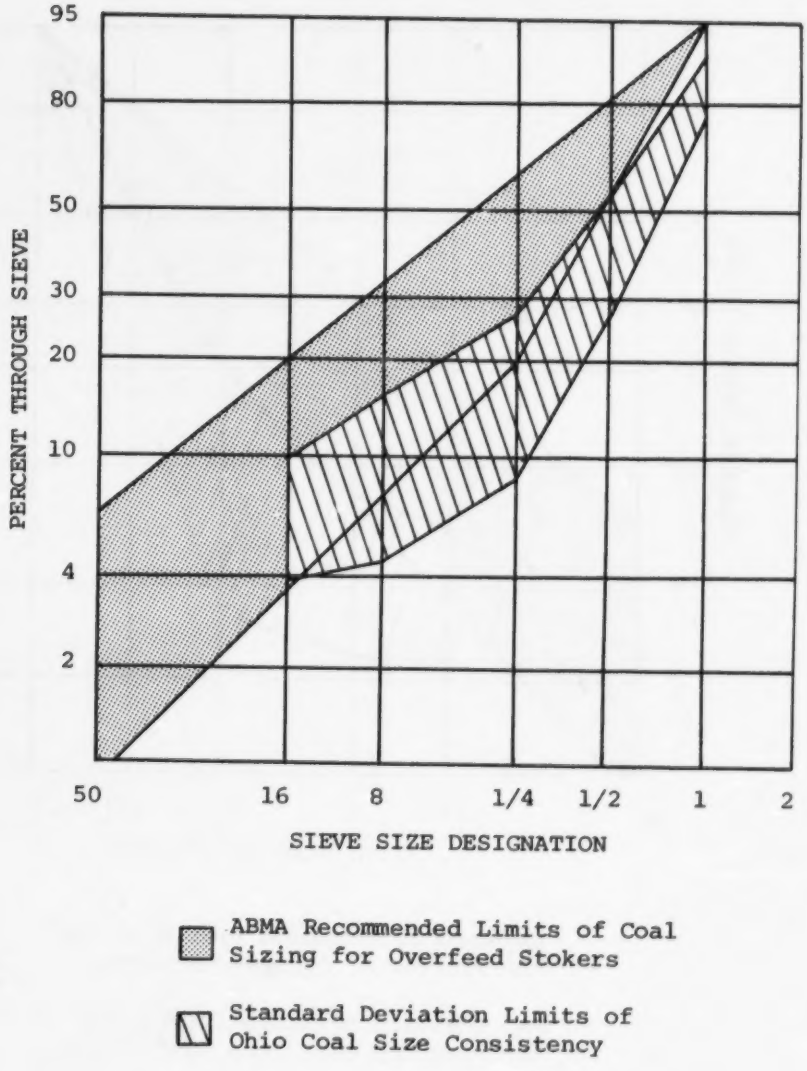


Figure 5-12. Size Consistency of "As Fired" Ohio Coal vs ABMA Recommended Limits of Coal Sizing for Overfeed Stokers - Test Site J.

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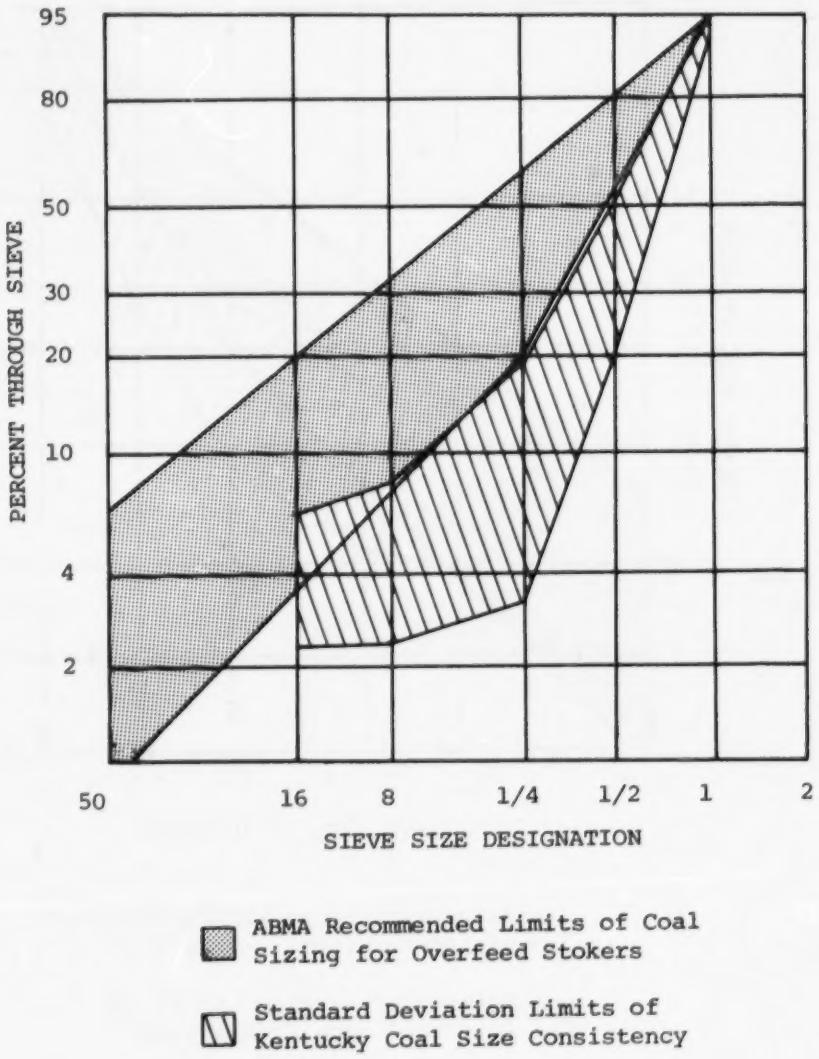


Figure 5-13. Size Consistency of "As-Fired" Kentucky Coal vs ABMA Recommended Limits of Coal Sizing for Overfeed Stokers - Test Site J.

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Particulate Mass Loading. There is no indication at either the boiler outlet or at the dust collector outlet that particulate emissions differed between the two coals. This conclusion is best illustrated in Figures 5-5 and 5-6 where the data is plotted as a function of grate heat release and differentiated as to coal.

Ash Carryover. The average ash carryover for burning Kentucky coal was 10.5% as opposed to 9.2% for Ohio coal. Because of the large variations in the data, this difference is not significant. In fact, Kentucky coal ash carryover ranged from 4.6% to 17.1% and Ohio coal ash carryover ranged from 5.8% to 13.5%.

Nitric Oxide. There is insufficient evidence to state that firing Kentucky coal resulted in a different level of nitric oxide emissions than when firing Ohio coal. The emission levels are similar for similar loads and oxygen levels. The data are presented in Figures 5-7 and 5-8.

Sulfur Dioxide. Sulfur dioxide ($SO_2$) and sulfur trioxide ($SO_3$) were measured in the flue gas during one test on each of the two coals. Along with the measured sulfur concentrations in the coal and bottom ash, a sulfur balance was attempted. The results, reflecting some inaccuracies in the data, are presented in Table 5-12. The source of the imbalance is not known.

TABLE 5-12

SULFUR BALANCE

| | Sulfur In Fuel lb/$10^6$Btu as $SO_2$ | Sulfur In Flue Gas lb/$10^6$Btu as $SO_2$ | Sulfur In Bottom Ash lb/$10^6$Btu as $SO_2$ | Sulfur In Flyash lb/$10^6$Btu as $SO_2$ |
|---|---|---|---|---|
| Ohio Coal (Test 16) | 3.110 | 2.819 | 0.038 | 0.004 |
| Kentucky Coal (Test 15) | 1.476 | 1.792 | 0.039 | 0.004 |

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Combustibles in the Ash. Combustible concentrations in the bottom ash were similar for both coals, averaging 20.6% for each. This data is presented in Figure 5-10. Combustible concentrations in the boiler outlet flyash averaged 25.0% for Ohio coal and 31.0% for Kentucky coal. This data is presented in Figure 5-9.

Boiler Efficiency. Boiler efficiency was higher while burning Kentucky coal by about 0.7%. One of the reasons for this difference was its lower moisture and hydrogen content. Table 5-13 presents the heat losses and boiler efficiency of two test sets where coal is the primary variable. Figure 5-11 presents the boiler efficiency data graphically as a function of grate heat release with coal type designated.

TABLE 5-13

BOILER EFFICIENCY VS COAL

| | HEAT LOSS, % | | | | BOILER EFFICIENCY % |
|---|---|---|---|---|---|
| | Dry Gas | Moisture Related | Combustible | Other | |
| Ohio Coal (Test 7) | 8.93 | 4.29 | 1.88 | 2.13 | 82.77 |
| Kentucky Coal (Test 8) | 7.98 | 3.94 | 2.46 | 2.23 | 83.39 |
| Ohio Coal (Test 13) | 8.98 | 4.65 | 1.74 | 2.03 | 82.60 |
| Kentucky Coal (Test 6) | 9.27 | 4.06 | 1.17 | 2.05 | 83.45 |

## 5.4 PARTICLE SIZE DISTRIBUTION OF FLYASH

Four particle size distribution determinations were made on the flyash emitted by Boiler J. The conditions under which these tests were conducted, and the methodology used, are given in Table 5-14. The results of these tests are summarized in Table 5-15.

The data obtained with a Brink cascade impactor are presented in Figure 5-14. These measurements were made simultaneously at the boiler outlet and at the stack after the dust collector and I.D. fan, under full load conditions while firing Ohio coal.

TABLE 5-14

DESCRIPTION OF PARTICLE SIZE DISTRIBUTION TESTS
TEST SITE J

| Test No. | Coal | Design Capacity % | $O_2$ | OFA | Sample Location | Particle Size Distribution Methodology Used |
|---|---|---|---|---|---|---|
| 13A | Ohio | 103 | 7.9 | 1.0 | Blr. Out | Brink Impactor |
| 13B | Ohio | 103 | 7.9 | 1.0 | Stack | Brink Impactor |
| 15 | Ky | 94 | 7.9 | 5.8 | Stack | SASS Cyclones |
| 16 | Ohio | 93 | 8.9 | 6.8 | Stack | SASS Cyclones |

TABLE 5-15

RESULTS OF PARTICLE SIZE DISTRIBUTION TESTS
TEST SITE J

| Test No. | Sample Location | SIZE DISTRIBUTION % Below 3 µm | % Below 10 µm | SIZE CONCENTRATION lb/$10^6$Btu Below 3 µm | lb/$10^6$Btu Below 10 µm |
|---|---|---|---|---|---|
| 13A | Blr. Out | 25.0 | -- | 0.25 | -- |
| 13B | Stack | 81.0 | -- | 0.80 | -- |
| 15 | Stack | 68.6 | 75.2 | 0.48 | 0.53 |
| 16 | Stack | 80.9 | 80.9 | 0.37 | 0.37 |

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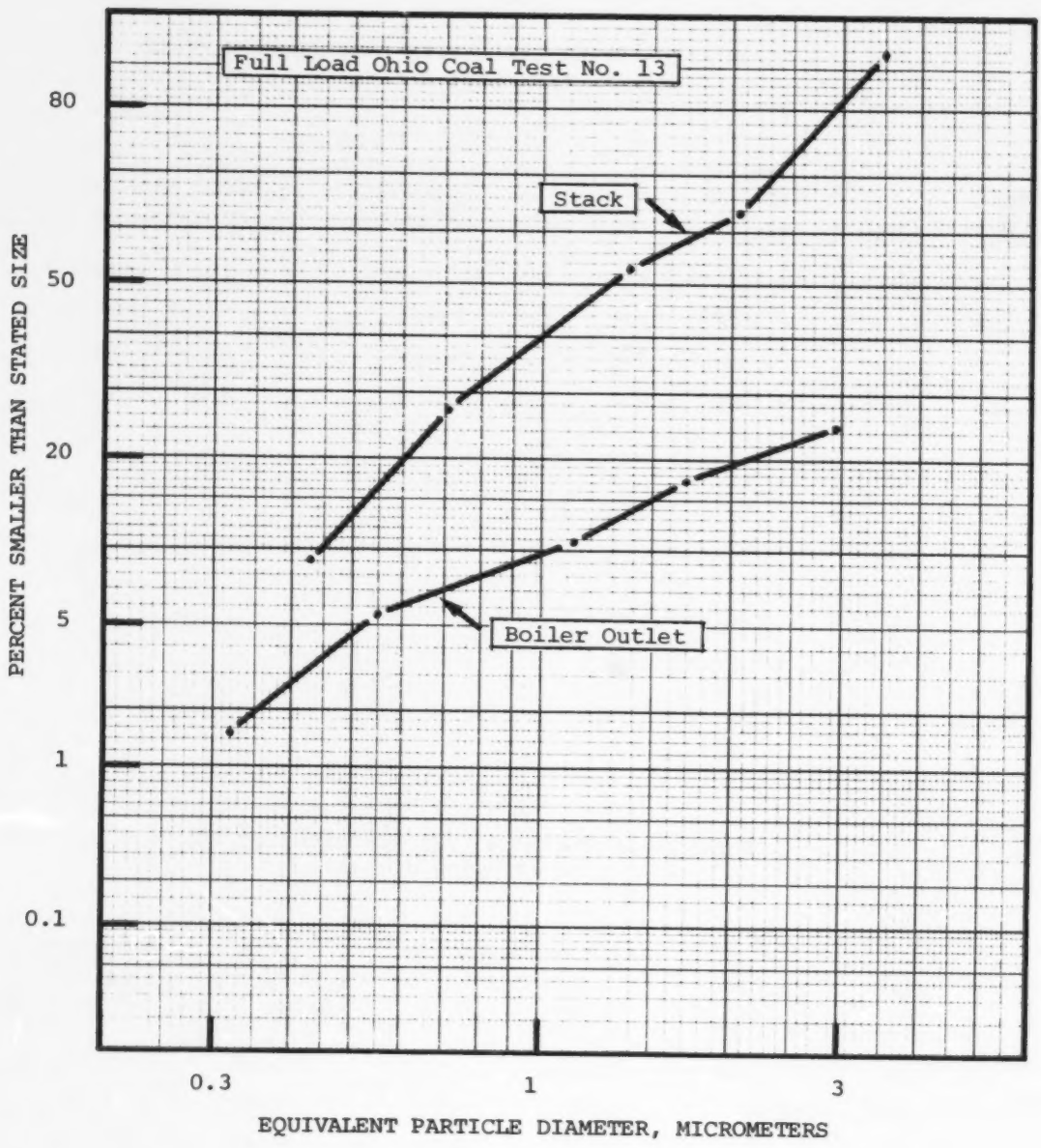


Figure 5-14. Particle Size Distribution at the Boiler Outlet and at the Stack by Brink Cascade Impactor - Test Site J.

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Figure 5-15 shows the results of two SASS cyclone measurements at the stack. Both of these tests were at full load, one on Ohio coal and one on Kentucky coal.

## 5.5 EFFICIENCY OF MULTICLONE DUST COLLECTOR

The collection efficiency of the multiclone dust collector was determined in eight tests under varying boiler operating conditions. The data were obtained by measuring the particulate loading simultaneously at the inlet and outlet of the dust collector. Test data are presented in Table 5-16 and plotted as a function of grate heat release in Figure 5-16.

The average measured dust collector efficiency was 74.3%. As mentioned previously in this report, the boiler outlet (collector inlet) particulate data is based on measurements in the upper third of the duct only. Therefore, this data may not be reliable. At the same time, however, it should be recognized that the boiler outlet particulate loading does fall in the expected range for overfeed mass fired stokers. Thus, any error is believed to be small.

## 5.6 SOURCE ASSESSMENT SAMPLING SYSTEM (SASS)

Two SASS tests were run at Test Site J. These two tests, no's 15 and 16, were conducted at full load and high overfire air on each of the two coals. The SASS samples have been processed by combined gas chromatography/mass spectroscopy for polynuclear content, seven specific polynuclear aromatic hydrocarbons (Table 5-17), and trace elements. All SASS test results will be reported under separate cover at the conclusion of this test program.

## 5.7 DATA TABLES

Tables 5-18 through 5-21 summarize the test data obtained at Test Site J. These tables, in conjunction with Table 2-2 in the Executive Summary, are included for reference purposes.

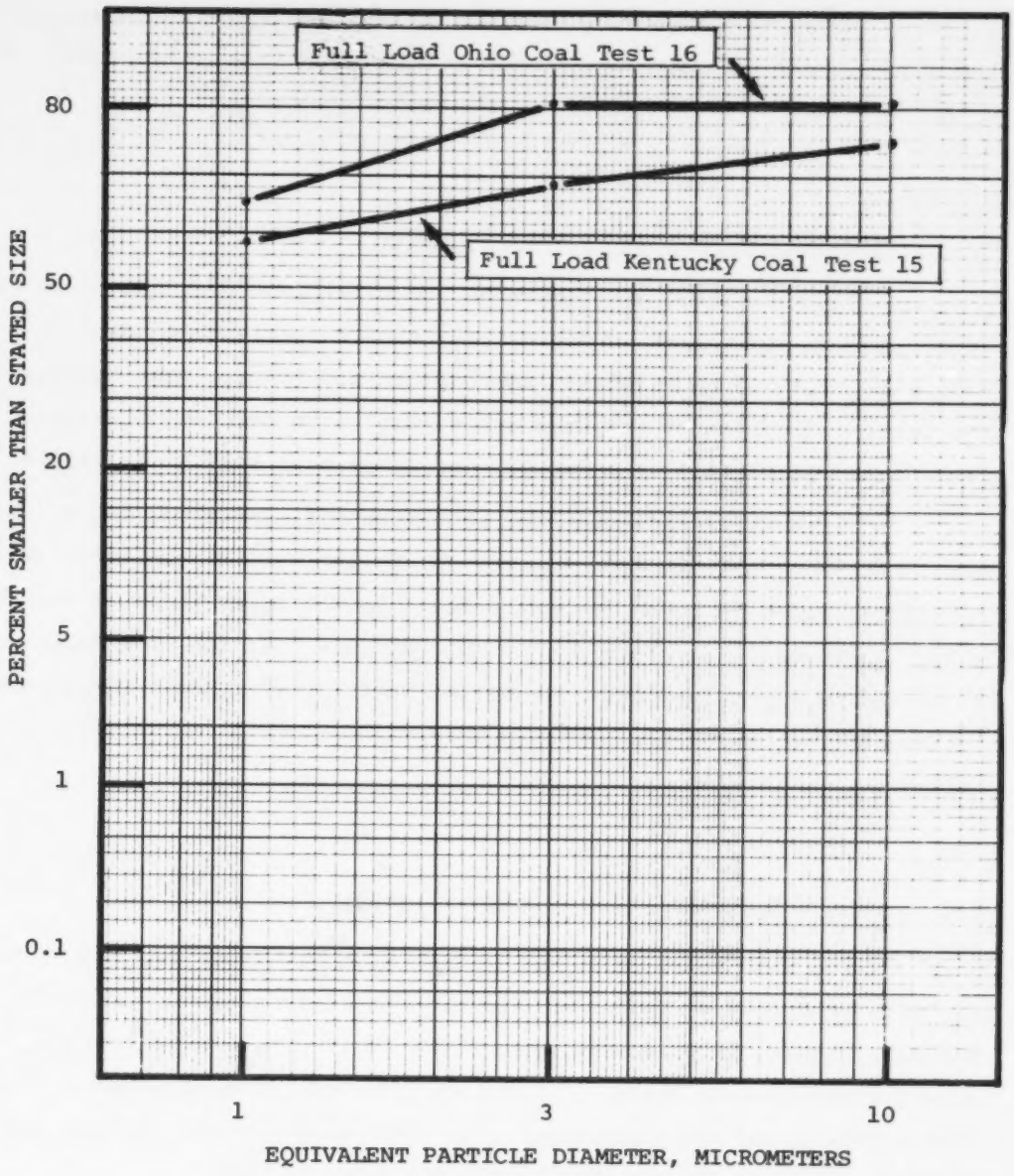


Figure 5-15. Particle Size Distribution at the Stack by Method of SASS Cyclones - Test Site J.

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TABLE 5-16

EFFICIENCY OF MULTICLONE DUST COLLECTOR
TEST SITE J

| Test No. | Coal Type | Load % | Particulate Loading Collector Inlet | lb/$10^6$Btu Collector Outlet | Collector Efficiency, % |
|---|---|---|---|---|---|
| 01 | Ohio | 48.2 | 0.369 | 0.115 | 68.8 |
| 02 | Ohio | 73.8 | 0.779 | 0.188 | 75.9 |
| 05 | Ohio | 102.6 | 1.442 | 0.228 | 84.2 |
| 06 | Ky | 98.6 | 0.699 | 0.182 | 74.0 |
| 07 | Ohio | 84.9 | 0.462 | 0.167 | 63.9 |
| 08 | Ky | 73.1 | 0.574 | 0.114 | 80.1 |
| 09 | Ky | 49.6 | 0.617 | 0.185 | 70.0 |
| 14 | Ohio | 97.1 | 0.984 | 0.224 | 77.2 |
| | | | | AVERAGE | 74.3 |

TABLE 5-17

POLYNUCLEAR AROMATIC HYDROCARBONS
ANALYZED IN THE SITE J SASS SAMPLE

| Element Name | Molecular Weight | Molecular Formula |
|---|---|---|
| 7,12 Dimethylbenz (a) anthracene | 256 | $C_{20}H_{16}$ |
| Dibenz (a,h) anthracene | 278 | $C_{22}H_{14}$ |
| Benzo (c) phenanthrene | 228 | $C_{18}H_{12}$ |
| 3-methyl cholanthrene | 268 | $C_{21}H_{16}$ |
| Benzo (a) pyrene | 252 | $C_{20}H_{12}$ |
| Dibenzo (a,h) pyrene | 302 | $C_{24}H_{14}$ |
| Dibenzo (a,i) pyrene | 302 | $C_{24}H_{14}$ |
| Dibenzo (c,g) carbazole | 267 | $C_{20}H_{13}N$ |

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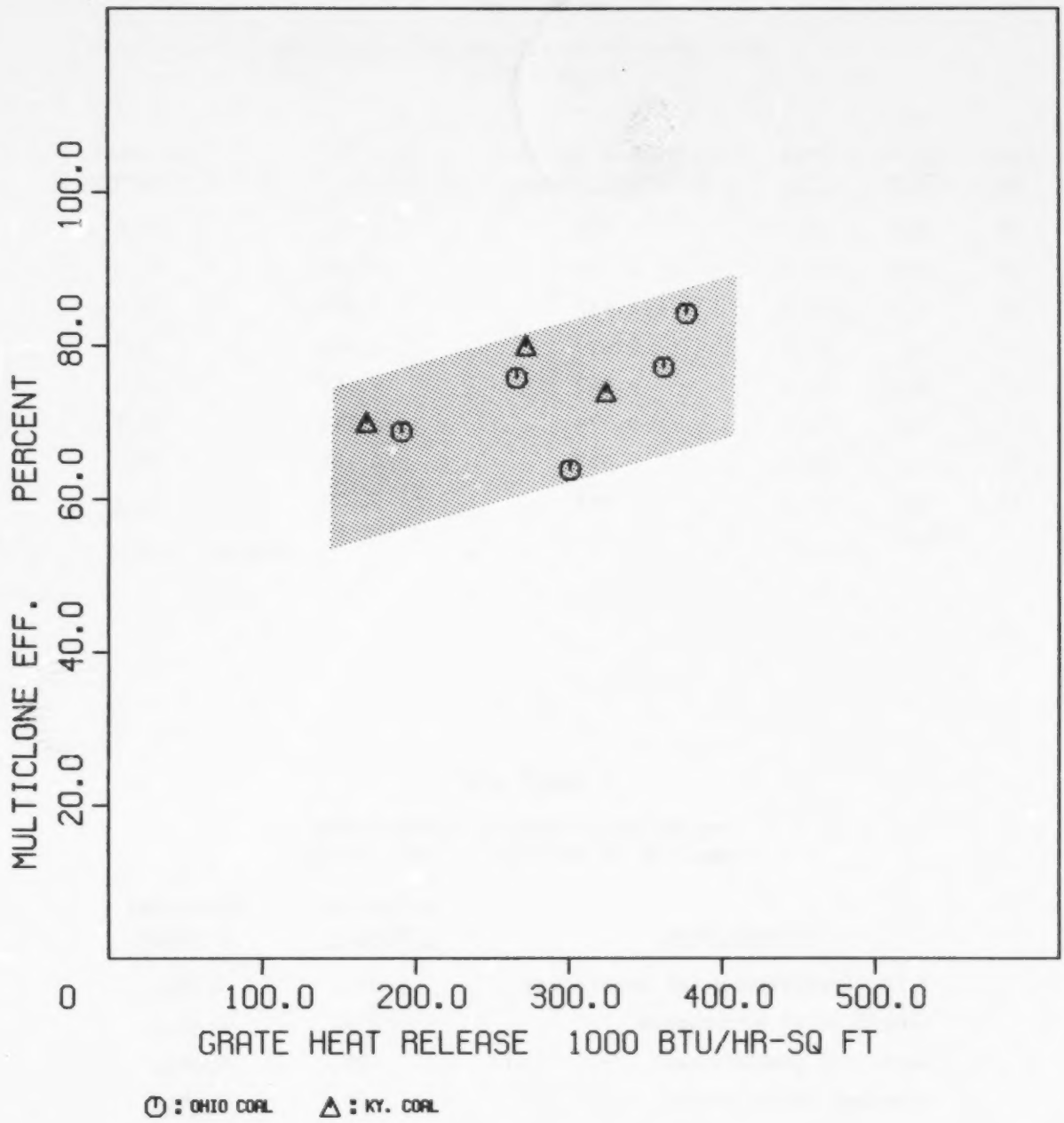


FIG. 5-16
MULTICLONE EFF. VS. GRATE HEAT RELEASE
TEST SITE J

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TABLE 5-18

PARTICULATE EMISSIONS
TEST SITE J

| | Test No. | Coal Type | Load % | $O_2$ % | EMISSIONS lb/$10^6$Btu | EMISSIONS gr/SCF | EMISSIONS lb/hr | Velocity ft/sec |
|---|---|---|---|---|---|---|---|---|
| BOILER OUTLET | 01 | Ohio | 48.2 | 10.2 | 0.369 | 0.137 | 15.0 | 33.96 |
| | 02 | Ohio | 73.8 | 10.6 | 0.779 | 0.276 | 44.1 | 53.47 |
| | 05 | Ohio | 102.6 | 7.9 | 1.442 | 0.602 | 115.6 | 62.67 |
| | 06 | Ky | 98.6 | 8.1 | 0.699 | 0.314 | 48.2 | 59.08 |
| | 07 | Ohio | 84.9 | 8.7 | 0.462 | 0.193 | 29.7 | 51.34 |
| | 08 | Ky | 73.1 | 9.0 | 0.574 | 0.240 | 33.2 | 40.87 |
| | 09 | Ky | 49.6 | 12.2 | 0.617 | 0.168 | 22.0 | 37.78 |
| | 14 | Ohio | 97.1 | 8.8 | 0.984 | 0.399 | 75.7 | 58.64 |
| DUST COLLECTOR OUTLET | 01 | Ohio | 48.2 | 9.7 | 0.115 | 0.045 | 4.68 | 20.23 |
| | 02 | Ohio | 73.8 | 10.8 | 0.188 | 0.065 | 10.6 | 30.62 |
| | 05 | Ohio | 102.6 | 8.3 | 0.228 | 0.092 | 18.3 | 33.68 |
| | 06 | Ky | 98.6 | 8.7 | 0.182 | 0.078 | 12.6 | 31.69 |
| | 07 | Ohio | 84.9 | 9.2 | 0.167 | 0.067 | 10.7 | 28.85 |
| | 08 | Ky | 73.1 | 9.2 | 0.114 | 0.047 | 6.60 | 21.42 |
| | 09 | Ky | 49.6 | 11.5 | 0.185 | 0.054 | 6.60 | 19.41 |
| | 14 | Ohio | 97.1 | 9.0 | 0.224 | 0.089 | 17.2 | 31.73 |

TABLE 5-19

PERCENT COMBUSTIBLES IN REFUSE
TEST SITE J

| | Test No. | Boiler Outlet | Multiclone Collector Hopper | Bottom Ash |
|---|---|---|---|---|
| OHIO COAL | 01 | 26.7 | 29.86 | 20.17 |
| | 02 | 24.9 | 12.09 | 15.47 |
| | 05 | 23.7 | -- | -- |
| | 07 | 24.7 | -- | 19.57 |
| | 13 | -- | -- | 18.58 |
| | 14 | -- | -- | 30.93 |
| | 16 | -- | -- | 18.97 |
| | AVG | 25.0 | | 20.62 |
| KENTUCKY COAL | 06 | 26.8 | -- | 20.26 |
| | 08 | 36.0 | -- | 30.75 |
| | 09 | 30.1 | -- | 7.23 |
| | 15 | -- | -- | 24.09 |
| | AVG | 31.0 | | 20.58 |

TABLE 5-20

HEAT LOSSES AND EFFICIENCIES
TEST SITE J

| TEST NO. | DRY GAS LOSS | MOISTURE IN FUEL | $H_2O$ FROM COMBUSTION OF $H_2$ | COMBUSTIBLES IN FLYASH | COMBUSTIBLES IN BOTTOM ASH | TOTAL COMBUSTIBLES IN REFUSE | RADIATION FROM BOILER | UNMEASURED | TOTAL LOSSES | BOILER EFFICIENCY |
|---|---|---|---|---|---|---|---|---|---|---|
| 01 | 11.26 | 0.25 | 3.93 | 0.14 | 1.58 | 1.72 | 1.10 | 1.50 | 19.76 | 80.24 |
| 02 | 11.77 | 0.28 | 4.09 | 0.28 | 1.22 | 1.50 | 0.73 | 1.50 | 19.87 | 80.13 |
| 05 | 9.54 | 0.40 | 4.11 | 0.49 | 2.42 | 2.91 | 0.53 | 1.50 | 18.99 | 81.01 |
| 06 | 9.27 | 0.17 | 3.89 | 0.27 | 0.90 | 1.17 | 0.55 | 1.50 | 16.55 | 83.45 |
| 07 | 8.93 | 0.26 | 4.03 | 0.16 | 1.72 | 1.88 | 0.63 | 1.50 | 17.23 | 82.77 |
| 08 | 7.98 | 0.16 | 3.78 | 0.29 | 2.17 | 2.46 | 0.73 | 1.50 | 16.61 | 83.39 |
| 09 | 11.48 | 0.27 | 4.21 | 0.26 | 1.00 | 1.26 | 1.07 | 1.50 | 19.79 | 80.21 |
| 13 | 8.98 | 0.44 | 4.21 | 0.06 | 1.68 | 1.74 | 0.53 | 1.50 | 17.40 | 82.60 |
| 14 | 9.36 | 0.29 | 4.15 | 0.35 | 3.54 | 3.89 | 0.56 | 1.50 | 19.75 | 80.25 |
| 15 | 8.84 | 0.18 | 3.85 | 0.30 | 1.78 | 2.08 | 0.57 | 1.50 | 17.02 | 82.98 |
| 16 | 10.66 | 0.28 | 4.20 | 0.40 | 1.72 | 2.12 | 0.58 | 1.50 | 19.34 | 80.66 |

## TABLE 5-21

## STEAM FLOWS AND HEAT RELEASE RATES
## TEST SITE J

| Test No. | Capacity % | Steam Flow lb/hr | Heat Input** $10^6$Btu/hr | Heat Output*** $10^6$Btu/hr | Front Foot Heat Release $10^6$Btu/hr-ft | Grate Heat Release $10^3$Btu/hr-ft$^2$ | Furnace Heat Release $10^3$Btu/hr-ft$^3$ |
|---|---|---|---|---|---|---|---|
| 1 | 48 | 33,766 | 40.7 | 40.3 | 2.91 | 191 | 10.2 |
| 2 | 74 | 51,652 | 56.6 | 61.7 | 4.04 | 266 | 14.1 |
| 3* | 100 | 70,000 | 76.7 | 80.0 | 5.48 | 360 | 19.1 |
| 4* | 100 | 70,000 | 76.7 | 80.0 | 5.48 | 360 | 19.1 |
| 5 | 103 | 71,822 | 80.2 | 85.7 | 5.73 | 377 | 20.0 |
| 6 | 99 | 69,016 | 69.0 | 82.5 | 4.93 | 324 | 17.2 |
| 7 | 85 | 59,463 | 64.2 | 71.1 | 4.59 | 301 | 16.0 |
| 8 | 73 | 51,200 | 57.9 | 61.1 | 4.14 | 273 | 14.5 |
| 9 | 50 | 34,699 | 35.7 | 41.4 | 2.55 | 168 | 8.9 |
| 13 | 103 | 71,719 | 69.4 | 87.7 | 4.96 | 326 | 17.3 |
| 14 | 97 | 68,000 | 77.0 | 81.2 | 5.50 | 362 | 19.2 |
| 15 | 94 | 65,760 | 71.8 | 78.6 | 5.13 | 337 | 17.9 |
| 16 | 93 | 64,808 | 67.5 | 77.3 | 4.82 | 317 | 16.9 |

* Tests 3 and 4, steam flows and heat release rates are estimated

** Heat input data based on coal weigh lorry readings and coal heating value

*** Heat Output data from steam tables

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## APPENDICES


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APPENDIX A

## CONVERSION FACTORS

### ENGLISH AND METRIC UNITS TO SI UNITS

| To Convert From | To | Multiply By |
|---|---|---|
| in | cm | 2.540 |
| $in^2$ | $cm^2$ | 6.452 |
| ft | m | 0.3048 |
| $ft^2$ | $m^2$ | 0.09290 |
| $ft^3$ | $m^3$ | 0.02832 |
| lb | Kg | 0.4536 |
| lb/hr | Mg/s | 0.1260 |
| $lb/10^6$BTU | ng/J | 430 |
| g/Mcal | ng/J | 239 |
| BTU | J | 1054 |
| BTU/lb | J/kg | 2324 |
| BTU/hr | W | 0.2929 |
| J/sec | W | 1.000 |
| J/hr | W | 3600 |
| BTU/ft/hr | W/m | 0.9609 |
| BTU/ft/hr | J/hr/m | 3459 |
| $BTU/ft^2/hr$ | $W/m^2$ | 3.152 |
| $BTU/ft^2/hr$ | $J/hr/m^2$ | 11349 |
| $BTU/ft^3/hr$ | $W/m^3$ | 10.34 |
| $BTU/ft^3/hr$ | $J/hr/m^3$ | 37234 |
| psia | Pa | 6895 |
| $"H_2O$ | Pa | 249.1 |
| Rankine | Celsius | C = 5/9R-273 |
| Fahrenheit | Celsius | C = 5/9(F-32) |
| Celsius | Kelvin | K = C+273 |
| Rankine | Kelvin | K = 5/9R |

FOR TYPICAL COAL FUEL

| | | | |
|---|---|---|---|
| ppm @ 3% $O_2$ ($SO_2$) | ng/J ($lb/10^6$Btu) | 0.851 | ($1.98x10^{-3}$) |
| ppm @ 3% $O_2$ ($SO_3$) | ng/J ($lb/10^6$Btu) | 1.063 | ($2.47x10^{-3}$) |
| ppm @ 3% $O_2$ (NO)* | ng/J ($lb/10^6$Btu) | 0.399 | ($9.28x10^{-4}$) |
| ppm @ 3% $O_2$ ($NO_2$) | ng/J ($lb/10^6$Btu) | 0.611 | ($1.42x10^{-3}$) |
| ppm @ 3% $O_2$ (CO) | ng/J ($lb/10^6$Btu) | 0.372 | ($8.65x10^{-4}$) |
| ppm @ 3% $O_2$ ($CH_4$) | ng/J ($lb/10^6$Btu) | 0.213 | ($4.95x10^{-4}$) |
| g/kg of fuel** | | | |

*Federal environmental regulations express NOx in terms of $NO_2$; thus NO units should be converted using the $NO_2$ conversion factor.

**Based on higher heating value of 10,000 Btu/lb. For a heating value other than 10,000 Btu/lb, multiply the conversion factor by 10,000/(Btu/lb).

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APPENDIX B

## CONVERSION FACTORS

### SI UNITS TO ENGLISH AND METRIC UNITS

| To Convert From | To | Multiply By |
|---|---|---|
| cm | in | 0.3937 |
| $cm^2$ | $in^2$ | 0.1550 |
| m | ft | 3.281 |
| $m^2$ | $ft^2$ | 10.764 |
| $m^3$ | $ft^3$ | 35.315 |
| Kg | lb | 2.205 |
| Mg/s | lb/hr | 7.937 |
| ng/J | $lb/10^6BTU$ | 0.00233 |
| ng/J | g/Mcal | 0.00418 |
| J | BTU | 0.000948 |
| J/kg | BTU/lb | 0.000430 |
| J/hr/m | BTU/ft/hr | 0.000289 |
| $J/hr/m^2$ | $BTU/ft^2/hr$ | 0.0000881 |
| $J/hr/m^3$ | $BTU/ft^3/hr$ | 0.0000269 |
| W | BTU/hr | 3.414 |
| W | J/hr | 0.000278 |
| W/m | BTU/ft/hr | 1.041 |
| $W/m^2$ | $BTU/ft^2/hr$ | 0.317 |
| $W/m^3$ | $BTU/ft^3/hr$ | 0.0967 |
| Pa | psia | 0.000145 |
| Pa | $"H_2O$ | 0.004014 |
| Kelvin | Fahrenheit | F = 1.8K-460 |
| Celsius | Fahrenheit | F = 1.8C+32 |
| Fahrenheit | Rankine | R = F+460 |
| Kelvin | Rankine | R = 1.8K |

FOR TYPICAL COAL FUEL

| | | |
|---|---|---|
| ng/J | ppm @ 3% $O_2$ ($SO_2$) | 1.18 |
| ng/J | ppm @ 3% $O_2$ ($SO_3$) | 0.941 |
| ng/J | ppm @ 3% $O_2$ (NO) | 2.51 |
| ng/J | ppm @ 3% $O_2$ ($NO_2$) | 1.64 |
| ng/J | ppm @ 3% $O_2$ (CO) | 2.69 |
| ng/J | ppm @ 3% $O_2$ ($CH_4$) | 4.69 |
| ng/J | g/kg of fuel | 0.000233 |

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APPENDIX C

## SI PREFIXES

| Multiplication Factor | Prefix | SI Symbol |
|---|---|---|
| $10^{18}$ | exa | E |
| $10^{15}$ | peta | P |
| $10^{12}$ | tera | T |
| $10^{9}$ | giga | G |
| $10^{6}$ | mega | M |
| $10^{3}$ | kilo | k |
| $10^{2}$ | hecto* | h |
| $10^{1}$ | deka* | da |
| $10^{-1}$ | deci* | d |
| $10^{-2}$ | centi* | c |
| $10^{-3}$ | milli | m |
| $10^{-6}$ | micro | μ |
| $10^{-9}$ | nano | n |
| $10^{-12}$ | pico | p |
| $10^{-15}$ | femto | f |
| $10^{-18}$ | atto | a |

*Not recommended but occasionally used

APPENDIX D

EMISSION UNITS CONVERSION FACTORS
FOR TYPICAL COAL FUEL (HV = 13,320 BTU/LB)

| To Obtain \ Multiply By | % Weight in Fuel | | lbs/$10^6$Btu | | grams/$10^6$Cal | | PPM (Dry @ 3% $O_2$) | | Grains/SCF. (Dry @ 12% $CO_2$) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | S | N | $SO_2$ | $NO_2$ | $SO_2$ | $NO_2$ | SOx | NOx | $SO_2$ | $NO_2$ |
| % Weight In Fuel — S | 1 | | 0.666 | | 0.370 | | $13.2\times10^{-4}$ | | 1.48 | |
| % Weight In Fuel — N | | | | 0.405 | | 0.225 | | $5.76\times10^{-4}$ | | .903 |
| lbs/$10^6$Btu — $SO_2$ | 1.50 | | 1 | | (.556) | | $19.8\times10^{-4}$ | | (2.23) | |
| lbs/$10^6$Btu — $NO_2$ | | 2.47 | | | | (.556) | | $14.2\times10^{-4}$ | | (2.23) |
| grams/$10^6$Cal — $SO_2$ | 2.70 | | (1.8) | | 1 | | $35.6\times10^{-4}$ | | (4.01) | |
| grams/$10^6$Cal — $NO_2$ | | 4.44 | | (1.8) | | | | $25.6\times10^{-4}$ | | (4.01) |
| PPM (Dry @ 3% $O_2$) — SOx | 758 | | 505 | | 281 | | 1 | | 1127 | |
| PPM (Dry @ 3% $O_2$) — NOx | | 1736 | | 704 | | 391 | | | | 1566 |
| Grains/SCF (Dry @ 12% $CO_2$) — $SO_2$ | .676 | | (.448) | | (.249) | | $8.87\times10^{-4}$ | | 1 | |
| Grains/SCF (Dry @ 12% $CO_2$) — $NO_2$ | | 1.11 | | (.448) | | (.249) | | $6.39\times10^{-4}$ | | |

NOTE: 1. Values in parenthesis can be used for all flue gas constituents such as oxides of carbon, oxides of nitrogen, oxides of sulfur, hydrocarbons, particulates, etc.
2. Standard reference temperature of 530°R was used.

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APPENDIX E

FLYASH COMBUSTIBLE CONTENT VS PARTICLE SIZE

Nine flyash samples were obtained from the mechanical dust collector hopper at Site J. Each sample was sieved with a 20 mesh screen, and the combustible content of each size fraction was determined. The data, presented below, indicate that the larger size fraction contains twice the combustibles content of the smaller size fraction on a mass percentage basis.

| Test No. | % Weight Passing 20 Mesh | % Combustible in Flyash Passing 20 Mesh | % Combustible In Flyash Larger than 20 Mesh |
|---|---|---|---|
| 5 | 81.9 | 20.84 | 26.62 |
| 6 | 77.5 | 20.64 | 36.38 |
| 7 | 83.8 | 19.85 | 36.97 |
| 8 | 81.4 | 23.16 | 53.86 |
| 9 | 82.7 | 20.62 | 44.55 |
| 13 | 85.6 | 20.67 | 51.37 |
| 14 | 77.0 | 19.31 | 26.76 |
| 15 | 82.9 | 22.45 | 53.06 |
| 16 | 86.9 | 22.94 | 59.97 |
| Average & Std Dev | $82\pm3$ | $21\pm1$ | $43\pm12$ |